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16. Abstract A crossed-field amplifier considered to be the first phase of a multi-phase program for the development of a suitable tube for use in the Solar Power Satellite was designed to meet the performance objectives of high signal to noise ratio, an efficiency of 85%, a CW microwave power output of 5-8 kW, and a frequency of 2450 MHz. The signal to noise ratio achieved was better than 69 dB/MHz in a 2000 MHz band centered on the carrier. High circuit efficiency of 97% and a sharp knee on voltage-current characteristic were achieved. The basic problem of maintaining good transfer of heat to the external radiator while providing for adequate connections to input and output was solved. Maximum efficiency achieved was 70.5% and gain and power level were below objectives. An investigation of causes of reduced performance indicated the poor field pattern in the cathode-anode interaction area of the tube was a major cause.			
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SUMMARY

The QKS1875 crossed field amplifier (CFA) development which is the subject of this report is closely related to meeting the requirements imposed upon a microwave generator by the Solar Power Satellite (SPS) concept in which microwaves are used to transmit energy captured from the sun by a satellite in synchronous orbit to the Earth's surface. These requirements include very high efficiency, very long life, a capability for dissipating the heat generated by any inefficiency directly into space by passive radiation, very low emission of power at any radio frequency outside of a guard band around the frequency allocated for the system, low mass requirements, and critical interfacing with the dc power input system. The work effort covered by this report is identified with the design, construction, and evaluation of a tube that is consistent with these requirements but which can be evaluated in a terrestrial environment.

The general performance objectives were a gain of 7 db, a CW microwave power added of 5-8 kilowatts, an efficiency of 85%, a high signal-to-noise ratio, to be achieved with a pure metal cathode at a frequency of 2.45 GHz, and with a design for dissipating heat that would be compatible with conversion to passive cooling in the space tube configuration.

Because of the great importance of a low level of both spurious (discrete frequency) and white noise outside of a protective guard band around the carrier, and because data for this kind of noise was unavailable on CW CFA's, the finding of a high signal to noise ratio over a ± 1000 MHz band around the carrier is considered to be very important and significant.

Other test data of importance to the space CFA development is the high circuit efficiency of over 97% and the very sharp "knee" on the voltage-current characteristic. The high circuit efficiency is essential to the hoped-for eventual realization of 90% overall efficiency for the microwave generator for the SPS. The sharp knee indicates a low value of leakage current and is essential for high efficiency at high values of DC input impedance and for low spurious noise. The data indicates that the space CFA could be scaled to considerably higher levels of DC voltage, if desired.

Another significant contribution was the solution of the problem of providing for adequate flow of heat from the CFA interaction area to an external radiator while providing connections to the input and output transmission lines which were adequately broad banded and rugged enough to handle the power levels anticipated for the tube.

Investigations of what may be considered a pioneering nature were made into the form of the microwave field pattern in the cathode-anode interaction area to explain the efficiency of 70.5% which was lower than the 85% expected, and to also explain the reduced gain and power level.

1.0 INTRODUCTION

The crossed field amplifier technology development with which this report is concerned is in support of meeting the requirements imposed upon a microwave generator by the power-from-space concept in which microwaves are used to transmit energy captured from the sun by a satellite in synchronous orbit to the Earth's surface. These requirements include very high efficiency, very long life, the capability for dissipating the heat generated by any inefficiency directly into space by passive radiation, very low emission of power at any radio frequency outside of a guard band around the frequency allocated for the system, low mass requirements, and critical interfacing with the dc power input system.

The effort covered by this report is considered to be the first phase of a multiphase effort to develop a crossed field amplifier tube to meet these objectives. It consists of the design, construction and evaluation of a tube which is to be consistent with the long range space-tube requirements, but which is liquid cooled, has a conventional vacuum envelope around it, and has its magnetic field supplied by an electromagnet rather than by a permanent magnet. In the evaluation of the tube, the efficiency and noise behavior are of particular importance. The data obtained from the development effort is intended to be used as a basis for further refinement of the tube design and for a more accurate definition of the base-line design of the microwave power transmission system.

In order to understand the design of this initial tube and the successive stages of development of the space-tube a substantial understanding of the concept of the Solar Power Satellite (SPS) and the microwave power transmission system is needed. Many of the interfaces to which the microwave generator is exposed are novel as well as exacting and must be appreciated to design a tube that will be compatible with them. The following sections are included as necessary background information.

1.1 The Solar Power Satellite (SPS) - Concept and Development

The solar power satellite (SPS) is a concept in which power is generated in a satellite in geostationary orbit and then beamed to earth in the form of a microwave beam which is then converted back into ordinary electrical power and distributed on a conventional power grid. Because the satellite is rotating at the same speed as the earth the microwave beam can be a continuous link to a specific location at the Earth's surface. The concept is particularly attractive in taking advantage of solar energy which is available over 99% of the time during the year, and only non-available for short durations of time of the order of an hour which occur near midnight during a period of 44 days during the autumnal and vernal equinoxes. Thus the electrical power derived from such a system is available on a predictable basis and can readily serve as a source of base load electrical power. The system eliminates the storage requirement which is an objectionable feature of an earth-based system for converting solar energy into electrical power.

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The general concept of the SPS was proposed by Dr. Peter Glaser in a paper (1) in Science in 1968 and immediately attracted considerable attention because of the concern, even then, about future sources of energy and their significance from an environmental impact point of view. The Glaser concept relied upon combining three basic technologies. These were the demonstrated photovoltaic cell technology for converting the sun's energy to electrical power, the demonstrated capability established by the space program to transport material from the earth into space, and the emergent and less known but demonstrated technology of transferring power by means of microwave beam (2, 3, 4, 5, 6, 7, 8,).

The first set of multi-authored published papers to be stimulated by interest in the Glaser concept is identified with the special December 1970 issue of the Journal of Microwave Power, entitled "Satellite Solar Power Station and Microwave Transmission to Earth" (9). It was obvious from a review of this set of stimulating but loosely related papers that an orderly, systematic, initial study of the complete concept from a system point of view was needed to evaluate its technical feasibility and to provide some initial inputs regarding its economic feasibility.

Such a feasibility study was undertaken by a group of personnel from four companies, identified as Arthur D. Little Inc., Raytheon Company, Grumman Aerospace Corp. and Spectrolab. Each of these companies published a technical volume representing its area of expertise. Together they covered the three areas of required technology as well as the socio-political aspects of the concept. This set of reports first indicated the technical feasibility of the concept and was an important motivating influence for the initiation of the first NASA sponsored studies.

It was apparent from the start of the four-company team study that the SPS system would present a tremendous challenge to the technology of microwave power transmission. In particular, the space portion of the system consisted of a mosaic of requirements, each of which would have to be met with a solution that was compatible with the other requirements. At that time requirements included very high efficiency, very long life (30 year), capability for dissipating the heat generated by any inefficiency directly into space by passive radiation, very low emission of power at any radio frequency outside of a guard band around the frequency allocated for the system, very low mass requirements, and critical interfacing of the microwave generator dc power input system, and the microwave radiating system of the antenna. The response to this challenge was a design concept for the microwave transmitter (10) which relied heavily upon a microwave generator approach which is the subject of this report.

Subsequently a contract was let in 1974 from Lewis Research Center (11) to further investigate the total microwave power transmission system and its relationship to the rest of the system. This study also concluded that the space portion of the microwave power transmission system was a most critical

issue and that the microwave generator was a key component and unavailable as a shelf item. Because of the long lead time required for microwave tube development it was recommended that the development work be initiated early.

This report is the result of the first phase of a proposed three phase development effort which was recommended for the Amplitron and which would result in a finished design compatible with the space environment upon completion of the three phase program.

Since the issuance of the RFP (request for proposal) for the subject work in January 1976, a number of developments, both technical and non-technical, have occurred which have impacted the direction of the development of the microwave generator. One of these is the general acceptance that there will be periodic on-board maintenance for the microwave generator and that an expected life time of 30 years or more will not be required.* While this relaxation may have occurred because of the limited life of a thermionic cathode required in other approaches to meeting the microwave generator requirements, it has a very important impact upon the design of the Amplitron as well. This impact has to do with decreasing the cathode backbombardment power, the method for disposal of the heat generated by this process, and reduced operating temperature of the proposed samarium-cobalt magnets.

Another development is the desire for higher operating voltages and power as a result of recent system studies that have been made. Both of these desires, taken in context with the technical results of the amplitron program covered by this report, are consistent with an easier starting and better operating amplitron-providing, of course, the mass of the cooling structure which goes up steeply with increased dissipation requirements does not prove to be a limiting factor.

Still another development has been the concept of an economical method of fabricating a thin-walled slotted waveguide radiator which can be attached to the Amplitron so that an integrated package results, and in which most of the power conditioning and phase compensation can also be intergrated. This concept is illustrated in Figures 1-4, and 1-5.

All of these developments, not anticipated at the initiation of the current amplitron development, have an important impact upon the conclusions and recommendations resulting from this work effort.

* Solar Power Satellite System Definition Study, Part III D180-24071-1
Preferred Concept System Definition, March 1978, Contract NAS9-15196
DRL T-1346 DRD MA664T

1.2 Adapting the Technology of Microwave Power Transmission to the SPS Application

1.2.1 Introduction

Microwave power transmission plays a crucial role in the SPS concept because there is no other known method which can transfer power from synchronous orbit to the Earth's surface regardless of atmospheric conditions at the high efficiencies that are needed to make the total system economically possible.

Microwave power transmission in the SPS, as it is in most applications, is a three step process. The first step is the efficient conversion of dc power into microwave power. The second step consists of properly distributing the microwave power over the transmitting aperture and then coherently radiating it to form a microwave beam which transports the energy to the receiving aperture. The final step is the reception of this microwave power and its conversion back into dc power.

The background technology (12) has developed to the point where overall dc to dc efficiencies of 54% have been documented in the laboratory (13) and significant amounts of power (30 kilowatts of received dc power) have been transmitted over a distance of one mile (14). It may also be shown that the basic technologies of the individual portions of the system can be increased or have already been increased to make laboratory efficiencies of close to 80% possible and efficiencies of 65% possible in the SPS concept (15).

With respect to adapting this background technology to the SPS it has been found that the adaptation of the technology of receiving the microwave power and converting it into dc power has been relatively straight forward with the principal concern being of an economic rather than a technical nature (16, 17). However, the SPS concept places an unusually severe set of requirements upon the satellite portion of the microwave power transmission system. The major requirements are:

1. The transmitter must get rid of any heat that results from any inefficiencies in the microwave generator, power conditioning, or transmission in the power busses by radiation into space.
2. The transmitter must have minimal weight in order to minimize transportation cost into space.
3. It must be possible to generate a highly coherent beam of microwaves from a very large aperture and point it with great precision.
4. The radiation from the transmitter must contain a minimum of energy that would cause radio frequency interference.

5. The transmitter must have a high degree of reliability and enough redundancy to make an unscheduled shutdown an event of very low probability.

A number of these requirements will be discussed in greater detail with their implication to the generator approach emphasized.

1.2.2 Radiation of Waste Heat in the SPS

The amount of microwave power that can be radiated from the transmitting antenna aperture per unit area is determined by the efficiency of the microwave generator and its associated power conditioning, and by the radiating temperature of the transmitting aperture. If it is assumed that the heat being radiated is spread uniformly over a black-body radiating area, then the microwave power that can be radiated follows the relationship

$$P = \frac{\eta}{1-\eta} \sigma T^4 A \quad (1)$$

where η is the combined efficiency of the microwave generator and the power conditioning

T is the temperature of the antenna surface

σ is the Stefan - Boltzman constant =

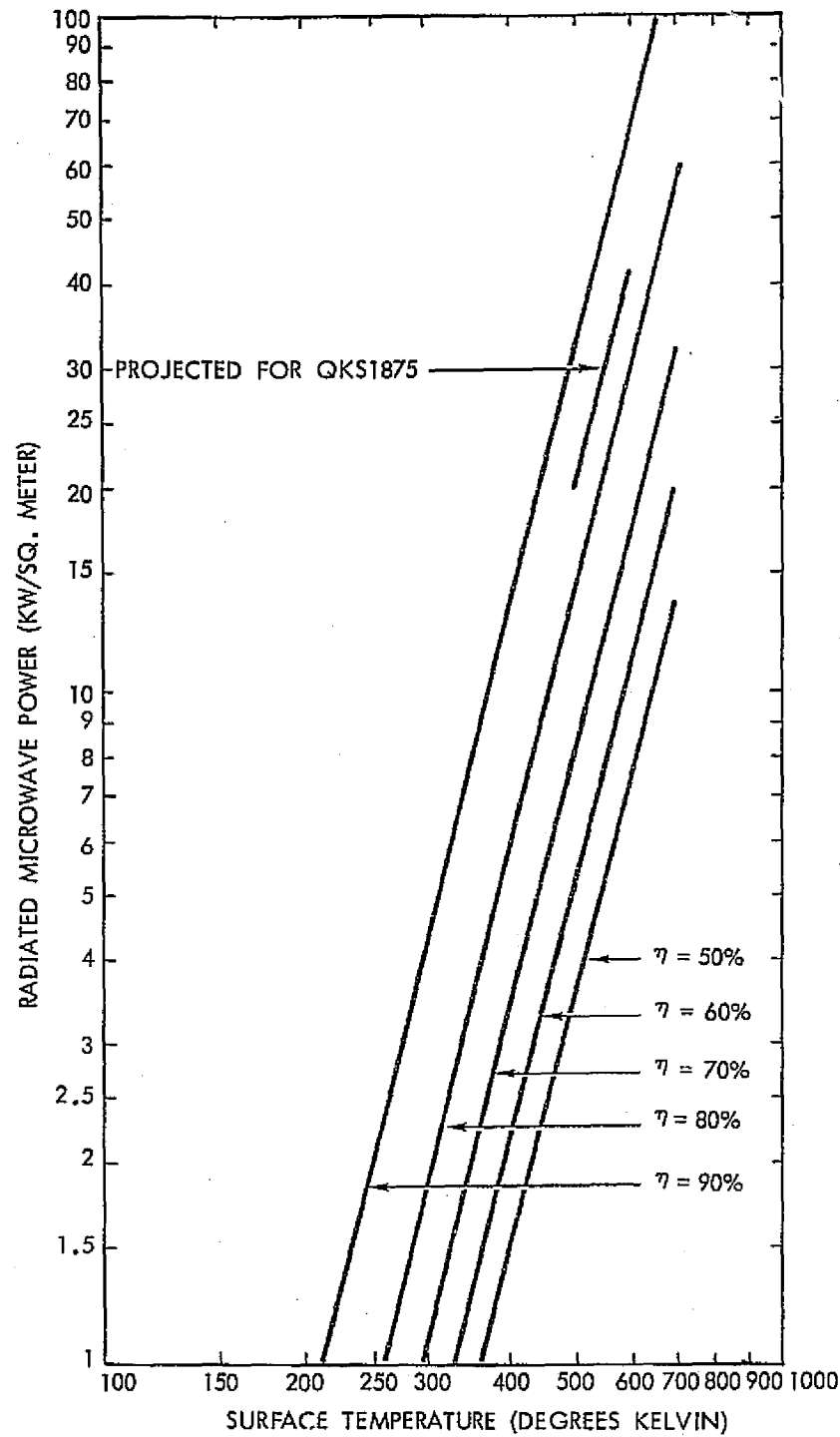
$$5.67 \times 10^{-8} \text{ watts Meters}^{-2} \text{K}^{-4}$$

A is the area

Figure 1-1 is a plot of the microwave power radiated per square meter as a function of temperature for various values of efficiency. For this figure black body radiation is assumed but some preferred radiators approach this situation.

Inspection of equation(1) and Figure 1-1 indicates that large amounts of microwave power can be radiated per unit area if both the efficiency and the radiating temperature are high. In this context it is noted that although high efficiency is always desirable, very high efficiency is primarily important in the SPS satellite because of the heat radiation problem.

Equation(1) is not adequate in itself to define the heat radiation problem in the SPS. This is because the mass required to transport heat from the area where it is generated to the area from which it is radiated may be considerable. The ideal situation would be to have the inefficiencies of microwave generation and power conditioning spread uniformly over the surface so that the resulting heat could be directly radiated without the need of mass to transport it. However, there are a number of factors which tend to prevent this ideal situation. One of the most important is that the more efficient microwave generators tend to be high power devices with the generation of heat concentrated



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Figure 1-1. Microwave power radiation density as a function of efficiency of microwave generator and temperature of antenna surface (one side only)

in small areas. If we are to use these devices then heat must be transformed to a large radiating area and if this is done by conduction it is found that the mass required for the heater transfer increases non-linearly, somewhere between the 2 and 2.5 power of the amount of heat to be transported.

Heat may also be transferred by means of heat pipes or by fluid flow to the surface of radiation but these means introduce many practical problems associated with active cooling in space where "active" is here defined as motion of a gas or liquid, whether or not outside energy is required for the motion.

1.2.3 The Generation of a Coherent Beam From a Large Aperture

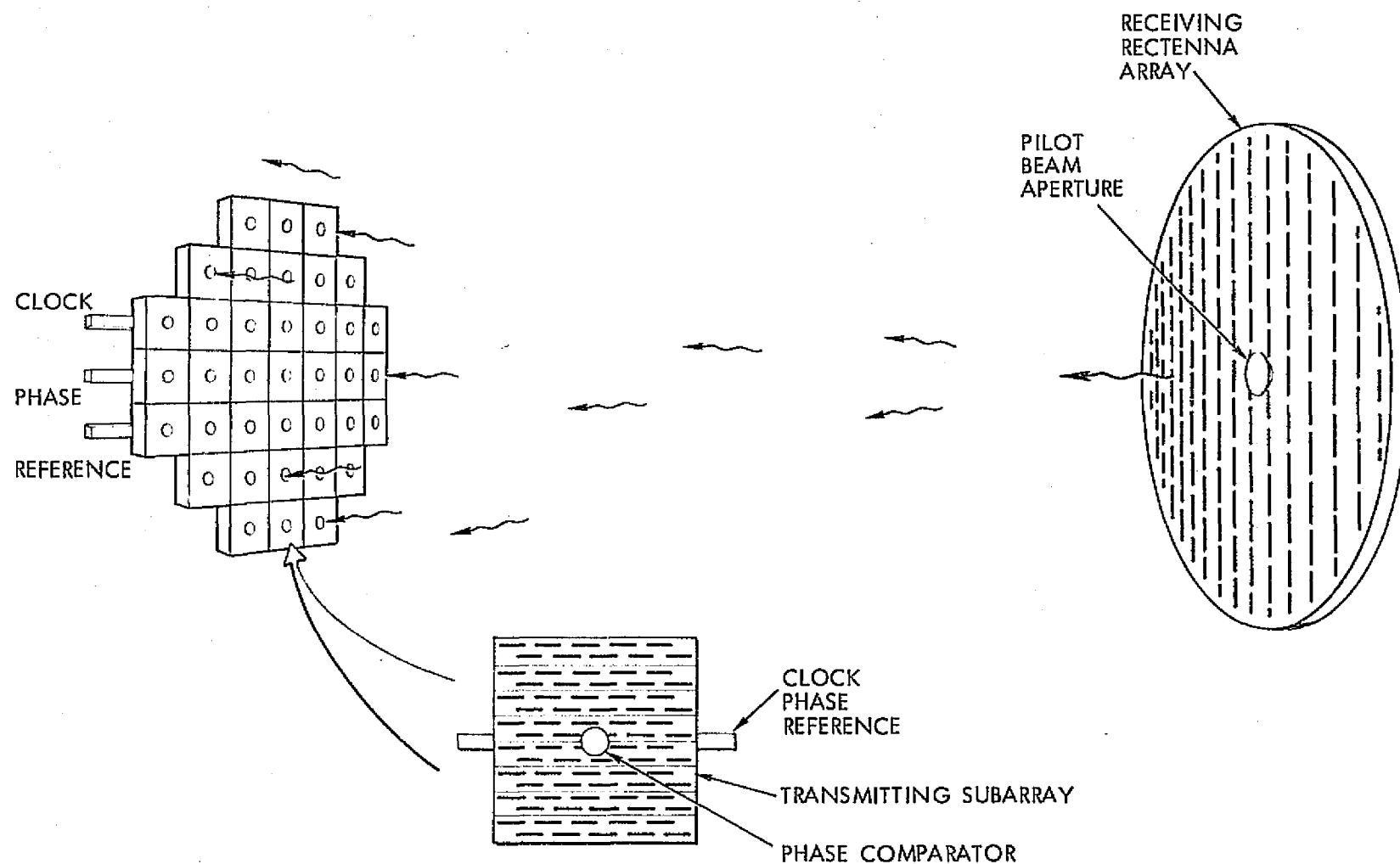
It is generally agreed that the best approach to this problem is the use of a retrodirective array. The principle of the retrodirective array is shown schematically in Figure 1-2. In this approach, the transmitting antenna is broken down into a large number of subarrays. At the center of the subarray is a means of comparing the phase of a signal that is generated within the transmitting antenna itself and which is everywhere identical at the phase comparison points (sometimes called the clock phase for this reason) with the phase of a signal which is sent from the center of the receiving array. The phase of the microwave power which is radiated from each subarray is the conjugate of the compared phase. When this procedure is carried out in all of the subarrays the result is coherent radiation of microwave power in a direction centered on the source of the pilot beam located in the center of the receiving site.

When this concept is applied to the transmitter in the SPS, it is found impractical to associate one microwave generator with each subarray. The complexity and cost of the phase control electronics must be spread out over a sizeable area which will contain many generators.

The exact size of the subarray has not been decided upon but areas of 100 square meters are typical of present thinking. With anticipated radiated microwave power densities of the order of 20 kilowatts per square meter, the total radiated power from the subarray would be of the order of 2000 kilowatts and because of the mass involved in the transportation of waste heat from the microwave generator to the radiator, as well as the relatively low capability of the waveguides to dissipate heat resulting from conducting large amounts of microwave power, the power level of the individual microwave generators is limited; as many as 400 generators may be required. The individual microwave generators must be spread out over the subarray and the phase of their emission somehow controlled from the phase comparison unit at the center of the subarray.

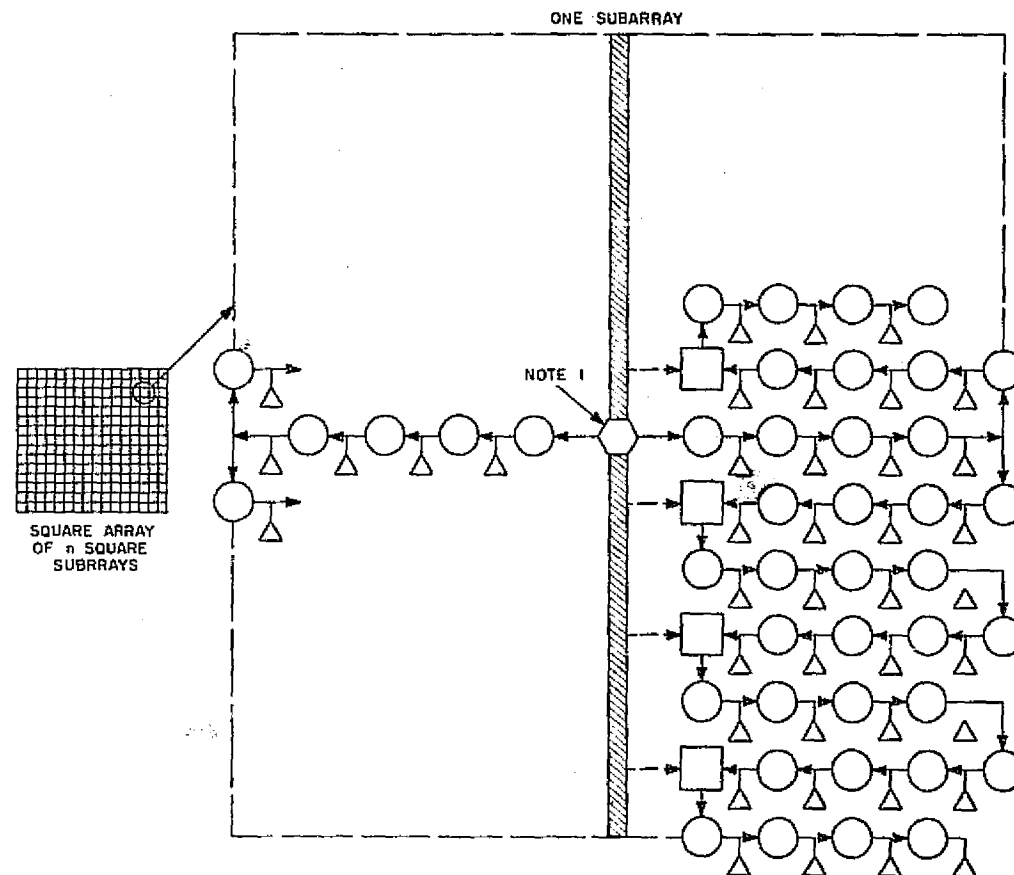
1.2.4 A Layout Format for the Subarray Containing Microwave Generators

Figure 1-3 shows a format for a subarray that will contain a large number of microwave generators of the amplatron type, although the format may have general applicability in any situation where a large number of generators must be used and where the phase of the output of these generators



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Figure 1-2. Diagram of Retrodirective Array. Pilot beam establishes a phase front reference at each subarray. This phase is compared with a clock phase which is the same at each comparison point. Each subarray then transmits with a phase that is the conjugate of the compared phase.



NOTE 1



CONSISTS OF:

INTERNAL PHASE REF.
SPACE-FED OR BY
TRANSMISSION LINE

ELECTRONIC
PHASE
SHIFTER

PILOT BEAM
PHASE
REFERENCE

HIGH GAIN
PREAMPLIFIER

AMPLITRON

TO SUBARRAY
CASCADE CHAIN

SYMBOLS



AMPLIFIER



ANTENNA RADIATING ELEMENT



PHASE COMPARATOR & CORRECTIVE
PHASE SHIFTER



REFERENCE PHASE TO COMPARATOR



CENTRAL SIGNAL SOURCE



PHASE REFERENCE SIGNAL FROM

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Figure 1-3. Proposed method for integrating microwave generators into a subarray which transmits with a phase controlled by the retrodirective array principle.

must be strictly controlled. The format of Figure 1-3 was developed to take advantage of a special property of the Amplitron which eliminates the need for a separate power supply for a thermionic cathode. This property is identified as the starting of current flow from a cold cathode when microwave energy of a sufficiently high power level is injected into the input of the tube. Any input power that is injected into the tube is added to the power generated within the tube and is therefore not lost. This permits operation of the Amplitron at a low gain level where the efficiency is highest and where the microwave input level is sufficiently high to start the flow of electrons from the cathode. All of the output power generated in each tube is radiated from a slotted waveguide, except for enough to drive the next Amplitron in the chain.

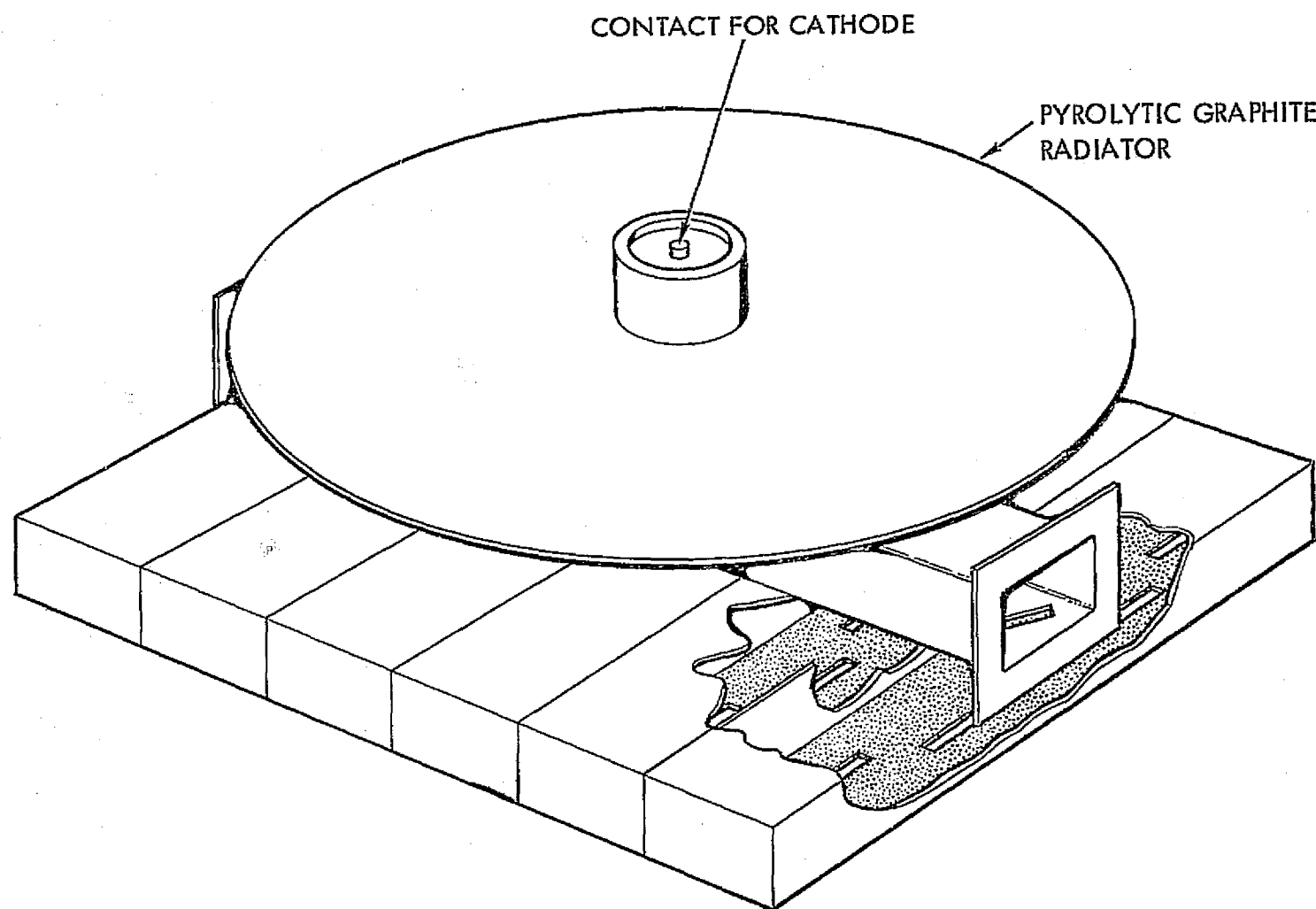
Phase correction as the microwaves energy is propagated along the structure will be necessary. In the format of Figure 1-3, this is accomplished as the wave propagates back to the center line of the array and compared with a reference phase at the center line. A number of options for phase correction may be considered. The phase correction may be divided equally among the units in cascade, if each unit is identical in its response to changes in the working environment.

The packaging concept for the unit may make this possible because of the uniformity of the packages and the trimming adjustments that can be made while each unit is under test. The packaging concept as shown in Figure 1-4 consists of the microwave generator, a radiator for radiating waste heat to space, and a section of slotted waveguide to radiate most of the power which the Amplitron generates. Enough power is left at the output flange of the unit to supply the next half section of slotted waveguide with power to radiate and to drive the next Amplitron. As discussed in section 1.2.5 there may be additional functions in the package to perform most of the power conditioning.

It may be possible that phase shift corrections for a known change in operating conditions can be programmed in an open ended fashion within the package itself, and that these corrections will be sufficiently small so that any accumulated error can be corrected with phase correction devices at the center line of Figure 1-3 only. The Amplitron device tends to run at near constant phase shift through the device even with shifting operating conditions so that phase corrections, although necessary, are relatively small.

However, if these two options are determined to be insufficient, a phase comparison may be made at each of the package units by running auxiliary reference transmission lines from the center line of the subarray.

Figure 1-5 shows how an assembly of the packages might appear in the transmitter. In this arrangement the package is virtually a plug in unit with only one electrical connection to it. The package is positioned with rails.



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Figure 1-4. A packaging concept for combining the microwave generator, its heat radiator, and a section of slotted waveguide radiator of nearly the physical size of the heat radiator. Microwave power feeding in at one wave guide flange supplies power to three "sticks" of radiating waveguide and power to drive the Amplitron. Output of Amplitron feeds three more "sticks" of radiating waveguide before reaching the output flange.

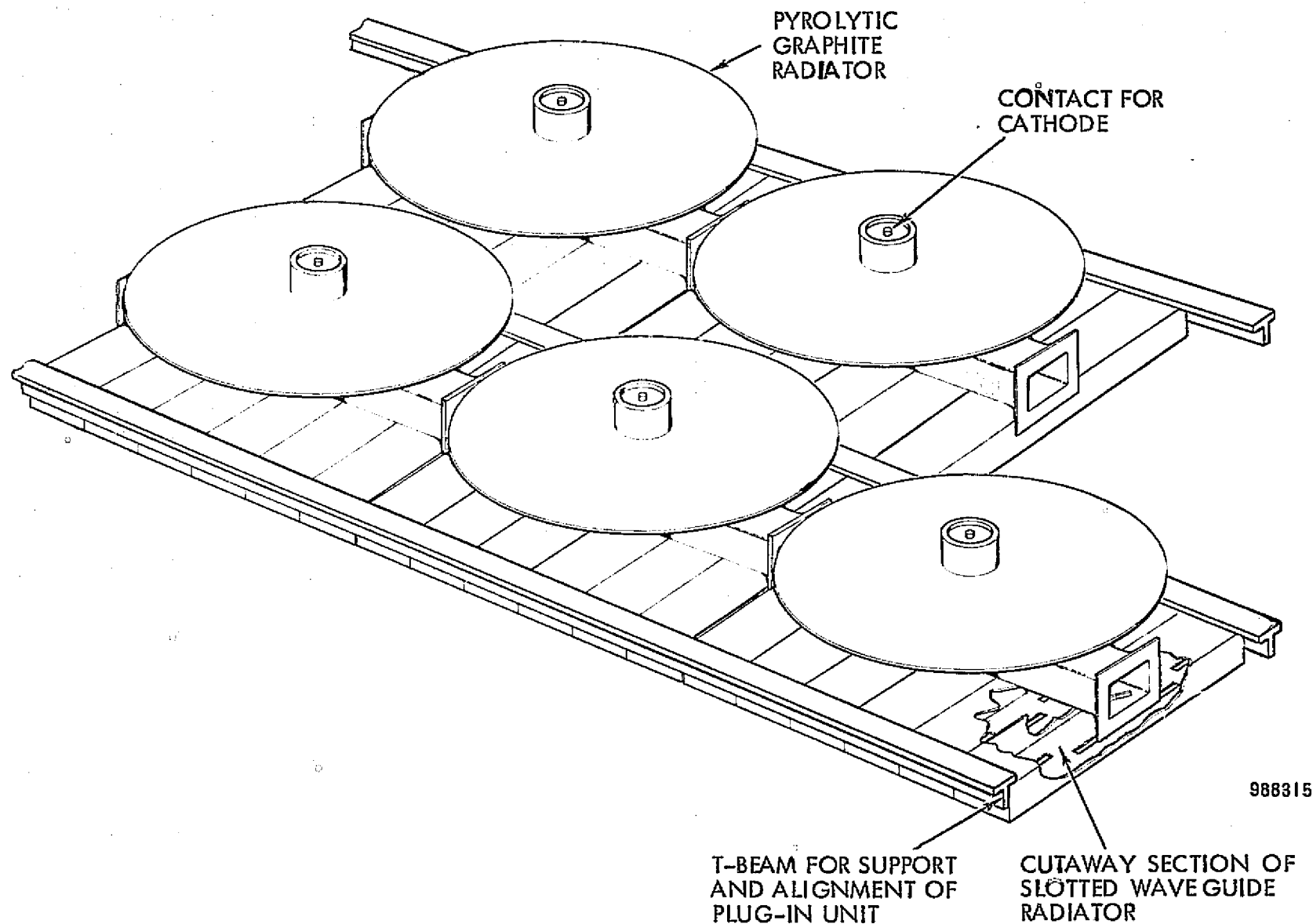
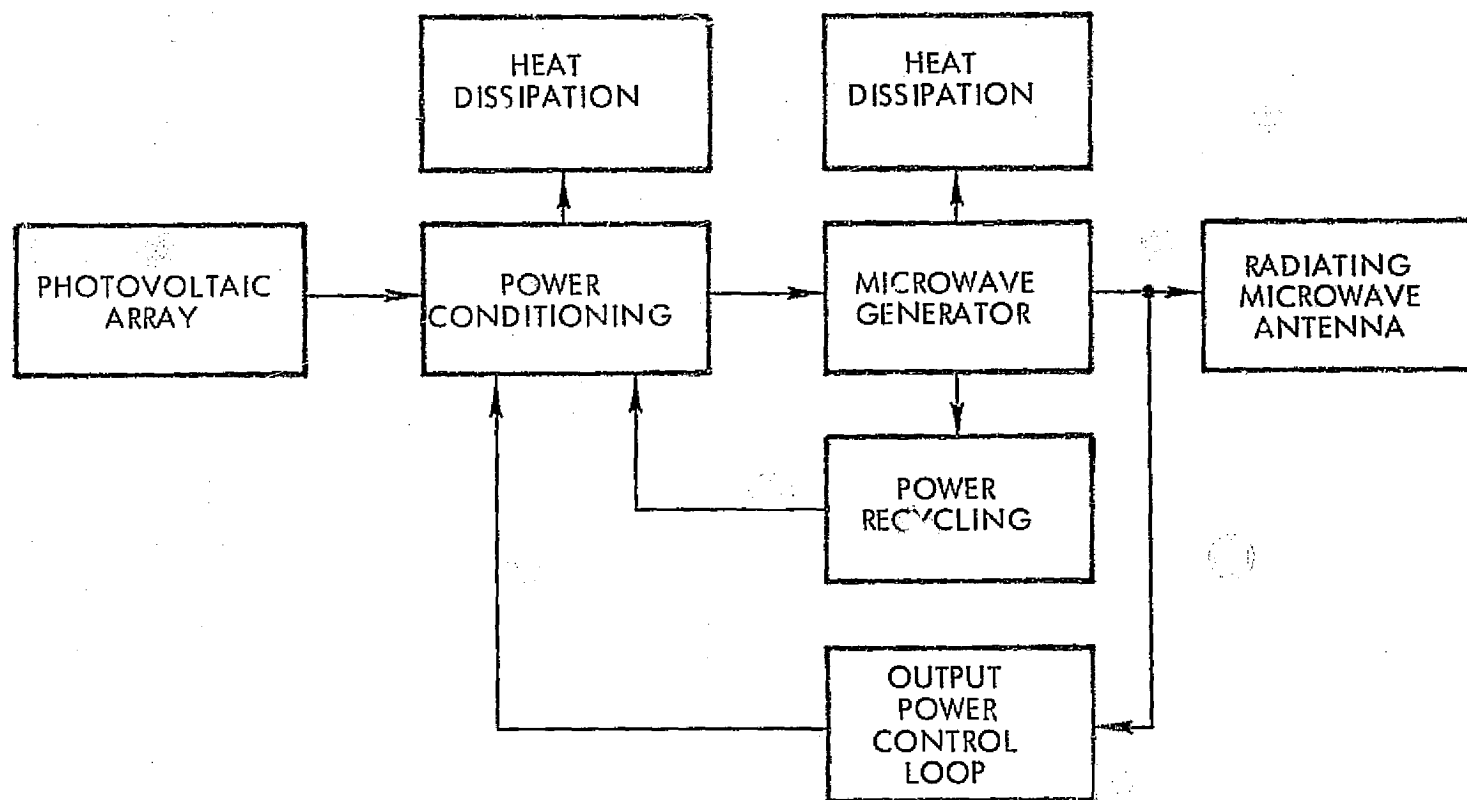


Figure 1-5. Assembly of packaged Amplitron and slotted waveguide units into a transmitting subarray. In this concept the packaged unit can be considered as a plugin unit that can be easily removed and replaced.



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Figure 1-6. Generalized interface of the microwave generator with the SPS microwave power transmission subsystem and the DC power bus.

Interface of the Microwave Generator with the Power Flow in the SPS and Amplitron Design Features to Accommodate This Interface.

Figure 1-6 shows the generalized interface of the microwave generator with the other portions of the satellite. On the input side of the generator there is a power conditioning interface through which the tube is connected to the photovoltaic array, while on the output side there is the interface to the radiating microwave antenna.

The power conditioning interface with the generator may consist of several elements. The number of elements will vary with the type of generator chosen. For the linear beam tube there will be a connection through which the dc input power flows to the tube, there will be a connection to a heating element in the thermionic emitting cathode, and probably one or more connections to the collector element to recycle some of the dc power and improve the efficiency. For the amplitron with a secondary emitting cathode which is started with the injection of microwave power the only connection to the power conditioning section is the one through which the dc power flows into the tube.

The power flowing into the radiating antenna from the tube must be controlled within close limits to maintain high efficiency of microwave power transmission. This implies a monitoring of the output power and sending a correcting signal back to some element which controls the flow of dc power into the generator. For a linear beam tube this control is frequently an additional element within the tube which performs as a power flow control.* If, for some reason this is not practical, then the power flow control must be in the power conditioning unit. In the case of the Amplitron the element within the tube which can control the power flow into the tube is the magnetic field. If it is not practical to vary the magnetic field to control the power flow then the power flow must be controlled in the power conditioning unit.

If the power conditioning unit is to control power flow into the tube it must provide the proper dc voltage to the tube. Since the power output of the photovoltaic array is also dc power, the power conditioning device is seen as a dc voltage changer. The dc voltage can be changed in two ways. In the first option, the dc voltage of the photovoltaic array can always be higher than that of the input to the microwave generator and the dc voltage reduction obtained by accepting a loss in a series resistance element in the power conditioning unit. In the second option the dc input power may be chopped up in such a manner that a voltage transformation, either up or down, is possible.

If the first option is chosen, there will be a decrease in overall efficiency but the real problem will be in getting rid of the heat which is produced in the power conditioning unit and which must be removed in an environment which is already running at several hundreds of degrees centigrade to dissipate the waste heat produced by the microwave generators.

* If substantial variations in efficiency with input voltage level can be tolerated the linear beam tube can be used without internal or external power conditioning. However, there will still be a need to control the uniformity of power output among tubes to maintain antenna radiating efficiency.

If the second approach is taken, a great deal of additional equipment and therefore mass is added to the satellite, there will still be some inefficiency, and the solid state devices with which such transformations are usually carried out, will not work properly in the high ambient temperature of several hundred degrees centigrade in which they will be immersed.

From this discussion it is seen that power conditioning is a critical element in the SPS satellite, and the manner in which the dc output of the photovoltaic array is matched to the microwave generator may well determine the technical feasibility of the complete SPS system.

The criticality of the interfacing of the microwave generator with the rest of the microwave power transmission system, including the input power conditioning, was early recognized by the author who suggested an approach in which varying the magnetic field of the amplatron was to be used to adjust the dc input power to the correct value to deliver a predetermined amount of microwave power to the radiating antenna. The control method does not result in any power dissipation aside from the few watts required to operate the control system, and in theory impacts the operating efficiency of the tube itself by less than one percent. Thus the output voltage from the solar array can vary a substantial amount and be accommodated without efficiency loss in the system and without significant addition of mass.

The generalized interface of the microwave generator with the SPS system, shown in Figure 1-6, can be particularized for the amplatron with a variable magnetic field as shown in Figure 1-7. All functions within the dotted line are a part of the Amplatron. Most of the power conditioning is carried on within the Amplatron package, leaving only the need to protect for an arc which may occur infrequently inside the tube. This protection will necessitate an external fuse or crowbar. In principle the fuse could be a very thin wire which connects the dc power bus with the tube. A crowbar would be far more complex and would also need the thin wire fuse to protect the crowbar if the arc in the tube did not clear with the momentary closure of the crowbar. The selection of the form of protection to be used for arcs may require a considerable amount of initial operating experience. The cause of these arcs is a complex subject in its own right. It is probable that substantial reduction of arcing would result from further research which would be motivated by need in this application. In this connection no arcing has been noted in testing present tubes but it will be a factor in all classes of tubes used in the high temperature space environment.

To understand the power conditioning feature which is carried on within the Amplatron package it is necessary to examine the interface between the solar array and the Amplatron. For this purpose it is helpful to superimpose the output characteristics of the solar photovoltaic array upon the input characteristics of the bank of Amplatrons, as shown in Figure 1-8. The input properties of the Amplatron generator used in the SSPS base-line design are distinguished from those of most other kinds of loads in that there is no current flow until a relatively high applied potential is reached, after which the current increases very rapidly with additional voltage. The solar array will be operated at maximum efficiency when the product of the voltage and current at its output terminal

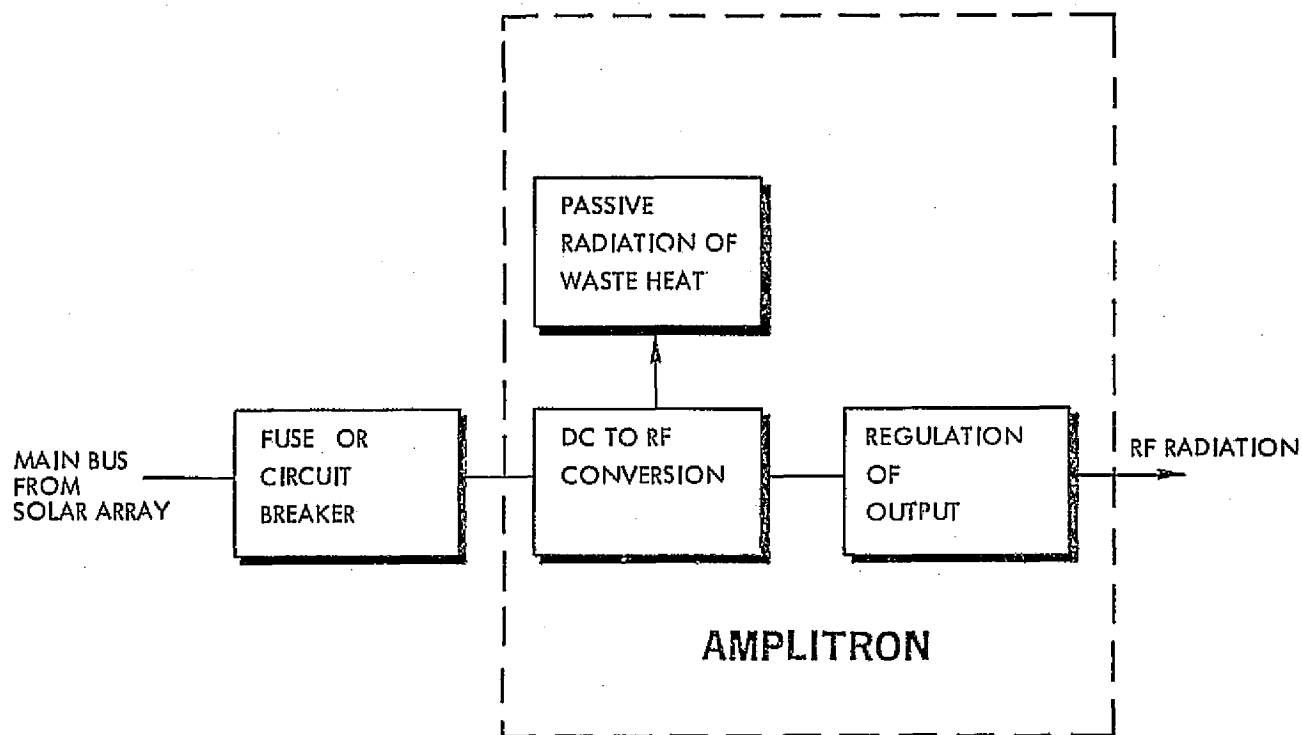


Figure 1-7. Specific interface for the packaged Amplitron device with the microwave power transmission subsystem and DC power bus. 870231

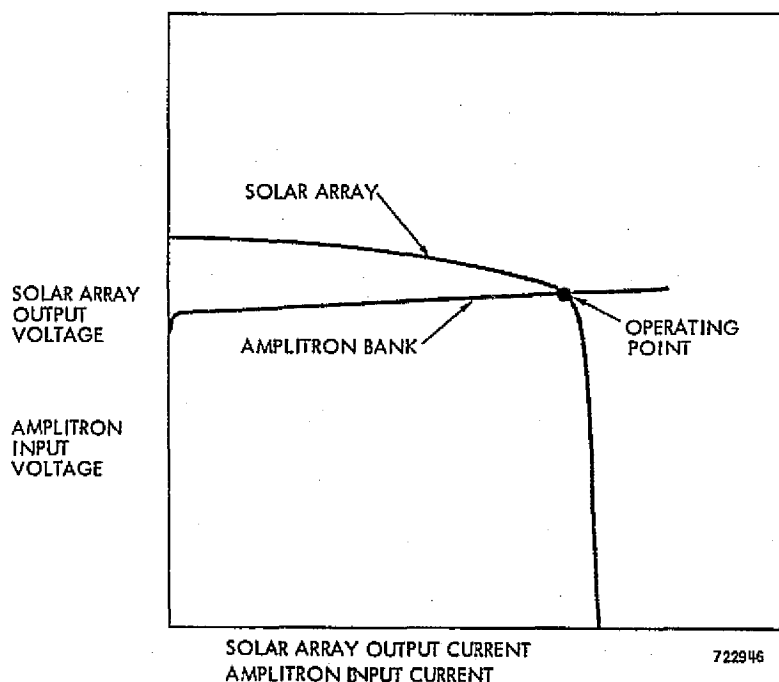


Figure 1-8. DC voltage and current characteristics of the Amplitron and solar photovoltaic array superimposed. 722946

is maximum. This should then coincide with the input operating point of the bank of generators.

The output of the solar cell array will be distributed to the Amplitrons on dc busses. The Amplitrons will be connected in parallel across the dc busses. Normally some kind of series regulator would be needed between the Amplitron and the dc buss as shown in Figure 1-9, not only because of uncontrollable residual variations in the characteristics of the individual tubes, but also because the microwave output of each Amplitron must be held to close tolerances for the efficient launching of the microwave beam. The regulator also must play a major role in the start-up of the system, where it is assumed that the initial start-up voltage will be greater than the normal operating voltages because of the regulation characteristic of the photovoltaic array as shown in Figure 1-8.

Fortunately the function of the series regulator which would dissipate power can be replaced by an adjustable magnetic field for the Amplitron which dissipates little if any power.

The relationship between input voltage, input current, and applied static magnetic field in the Amplitron is shown in Figure 1-10. If the applied voltage is too high, the magnetic field can be raised and the current flow reduced to obtain the same input power. Similarly, if the applied voltage is reduced, the magnetic field can be lowered and the current flow increased to obtain the same input power.

The magnetic field in the Amplitron can be varied electrically by utilizing a solenoid to produce flux which will add to or subtract from the flux established by the permanent magnet material, or mechanically by moving one or both of the pole pieces in the Amplitron as shown schematically in Figure 1-11. The latter method is the best from a power consumption point of view. The desired result can be accomplished by the expenditure of no more than four or five watts of dc power which can be obtained by efficiently rectifying a small amount of microwave power extracted from the Amplitron output.

There is an intuitive objection to mechanical bearings in space, which the mechanical motion of the poles implies, because of the lack of conventional lubrication. However, it should be noted that millions of X-ray tubes have been manufactured with high speed bearings which are completely within the vacuum. The requirement placed upon the SPS application is for only intermittent operation at relatively low speeds. There are a number of interesting approaches to the movement of the pole pieces for this application, and the arrangement in Figure 1-11, which is little more than schematic, would not necessarily be used.

The movement of the pole pieces can be combined with a power sensor at the output of the Amplitron to form a control loop that will adjust the microwave output of the Amplitron to a predetermined level over a wide range of bus bar voltage. The control system is shown schematically in

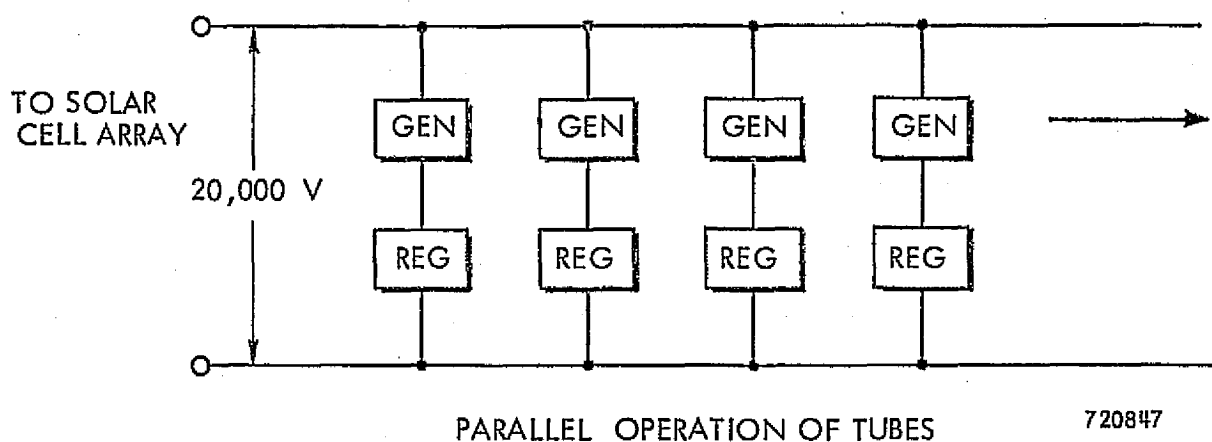


Figure 1-9. Schematic diagram indicating parallel operation of Amplitrons across a DC bus and the need for regulating the power input into each Amplitron.

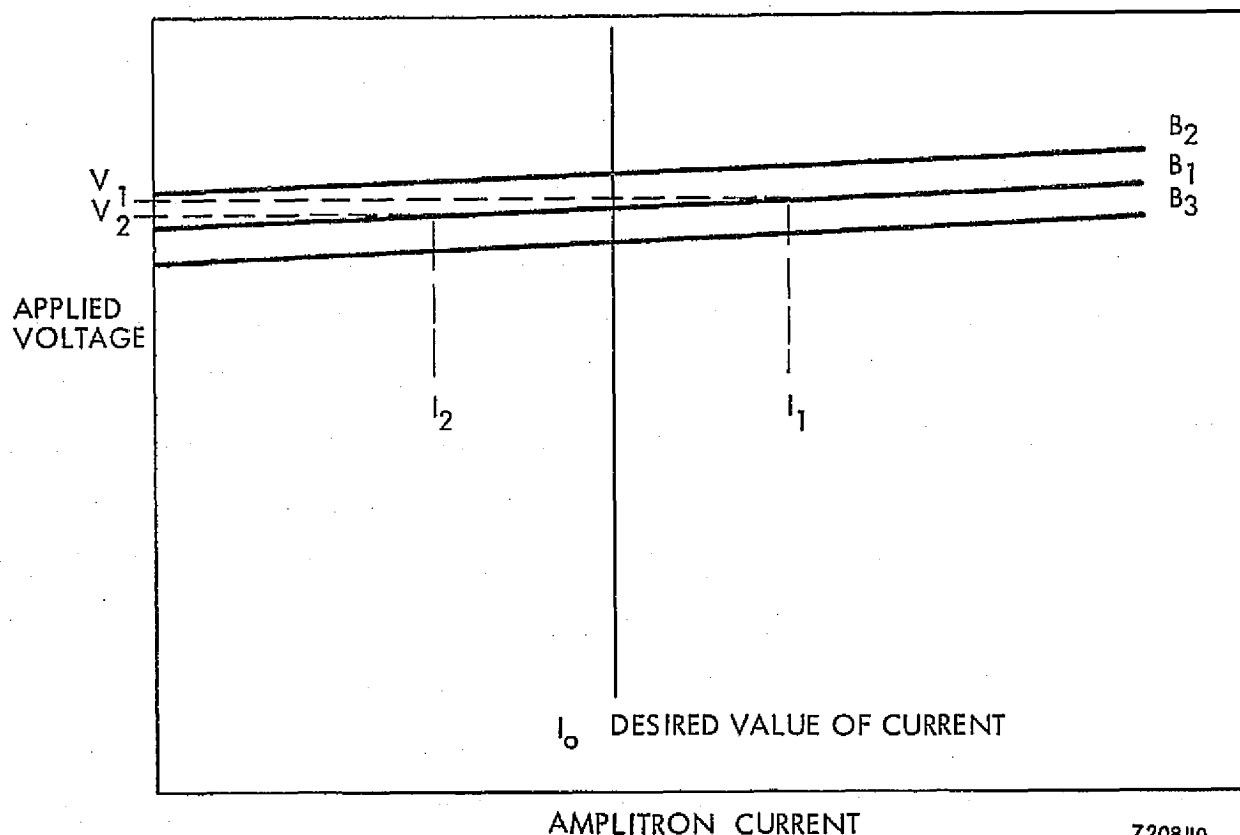
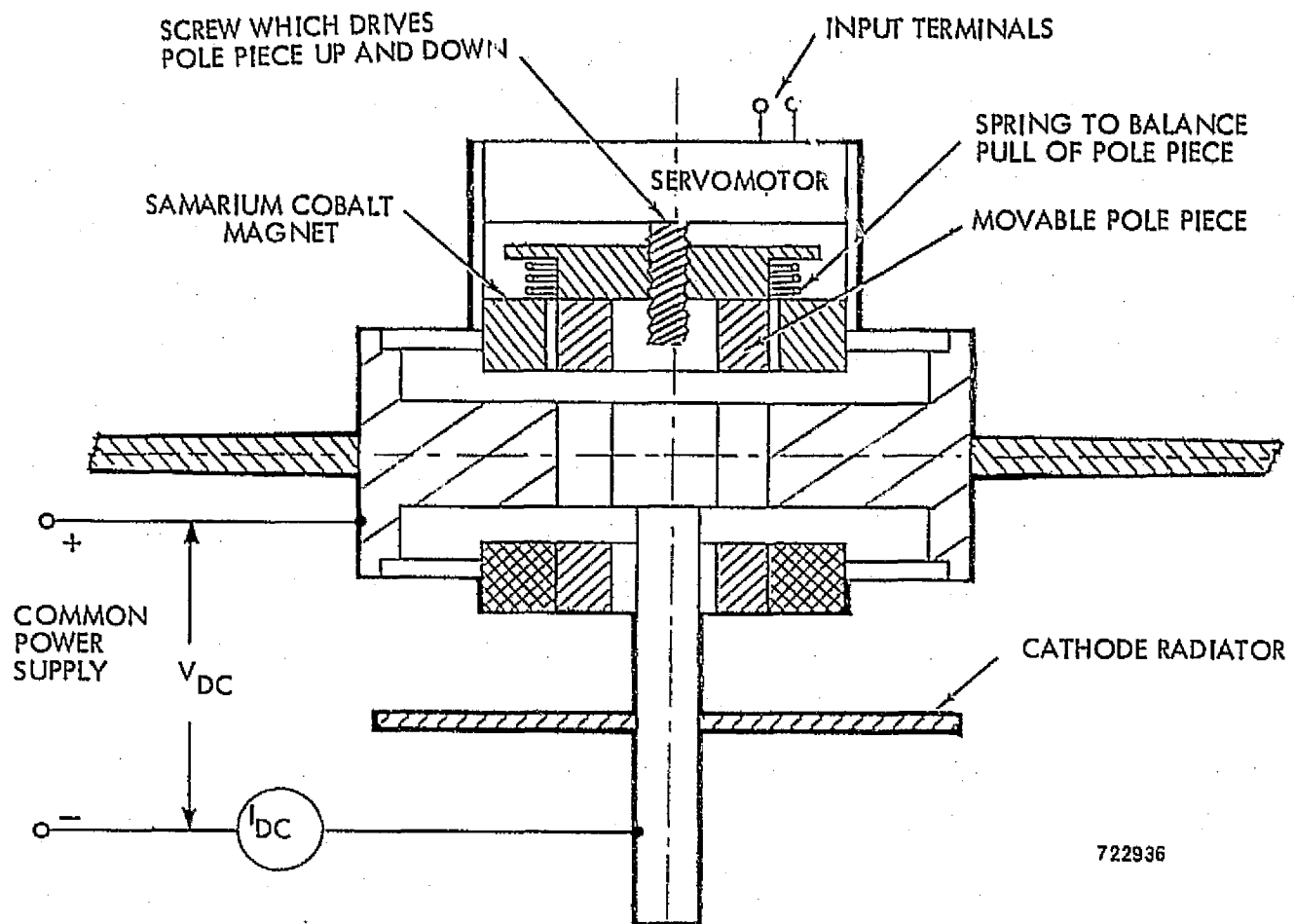


Figure 1-10. DC input characteristics of Amplitrons. B_1 , B_2 , and B_3 are different values of magnetic field. If the applied voltage were to vary, the magnetic field could be adjusted to maintain the desired value of current input or, if desired, a constant value of microwave power output using the arrangement of Figure 1-12.

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Figure 1-11. Cross section of an Amplitron with a movable pole piece to change the magnetic field.

Figure 1-12. The control system consists of a reference voltage which corresponds to the desired value of microwave output, and an error feed back system which compares the actual microwave output with the desired value and then changes the magnetic field in the tube to reduce the error at the output.

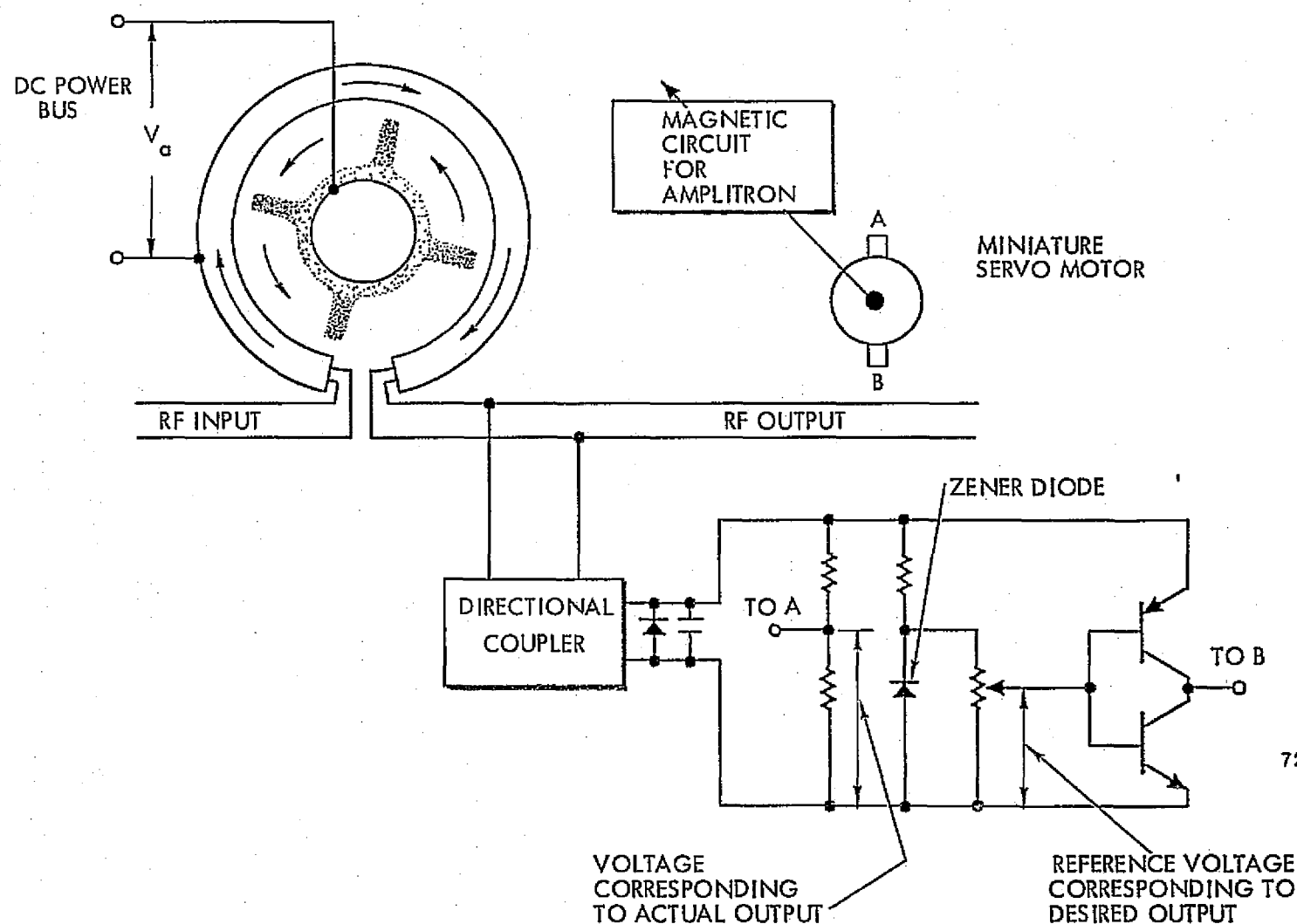
The entire control loop can be actuated without auxiliary electric power, as suggested in Figure 1-12.

The directional coupler extracts energy from the line and energizes a zener diode which sets a voltage reference level which is compared with the input level from the directional coupler to provide an error signal. The error signal actuates a motor to change the magnetic field so that the microwave power output is restored to its proper level. The motor, consuming a few watts of energy only while it is being intermittently operated, also obtains its energy through the directional coupler.

Since the desired output level may vary as a function of time it may be necessary to set the reference output level from an external source. However, this can be carried out at very low levels of signal power.

Thus far, the control of the output of the Amplitron and the interface with the solar array have been examined under the assumption that the Amplitron is operating. Actually, the operation of an Amplitron with a cold secondary emitting cathode will not begin - even though the proper voltage is applied - until microwave power is injected into the microwave input of the tube. When microwave power is injected into the tube, it starts almost instantly, far too fast for the feedback control system to be effective. If the applied voltage is too high, there will be a surge of current through the tube with disruptive consequences. Therefore, when the system is shut down for any reason, it will be necessary to automatically latch the pole pieces in a position where the resulting magnetic field will be great enough to preclude any current from being drawn initially when the system is turned on again. Then, when microwave drive power is again applied to the Amplitron the microwave power sensor at the Amplitron output will sense this and unlatch the control circuit. The current in the tube will begin to flow as the control circuit reduces the magnetic field and will be brought up smoothly to the operating point within a few milliseconds.

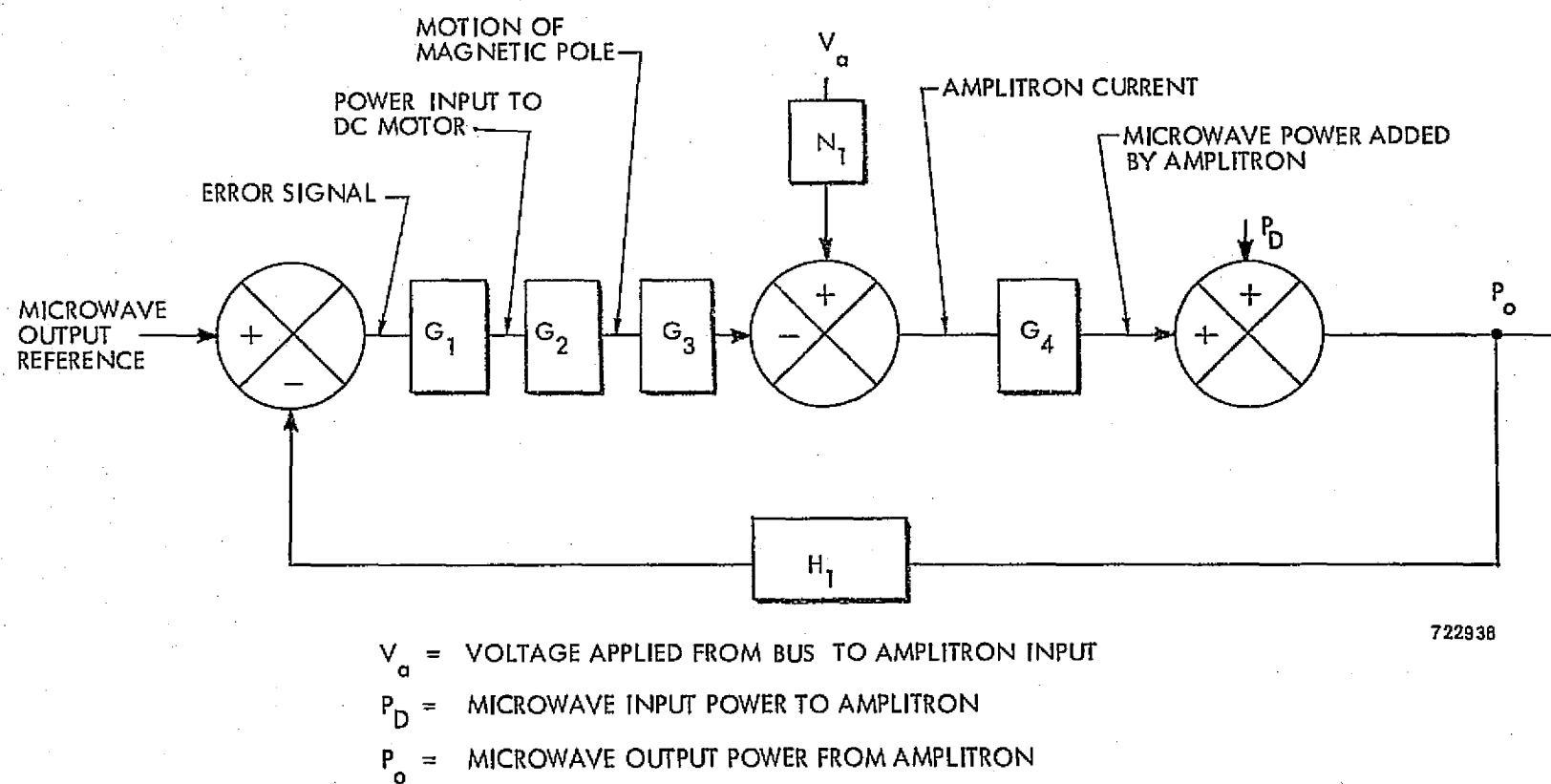
The various transfer functions in Figure 1-13 have been worked out and an expression for the complete openloop transfer function has been developed for probable values of the weight of the moveable pole piece and the spring compliance necessary to restrain the pole piece for the original proposed design. Typical response times with an appropriate lead network appears to be about 10 milliseconds. The gain of the system is highly dependent upon the slope of the voltage - current characteristic of the amplitron and will impact the amount of electronic gain needed for the system.



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Figure 1-12. Schematic circuit indicating how power can be tapped off of output of Amplitron and rectified to (1) supply a reference signal for controlling the output, (2) supply power for the control system including power for a motor to move the pole pieces.



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Figure 1-13. Control circuit schematic for maintaining a predetermined level of microwave power output from the Amplitron in the SSPS, in the presence of external disturbances such as variation in power supply voltage, changes in operating temperature of the tube, dimensional changes related to life, etc.

1.3 Background Information on Amplitrons

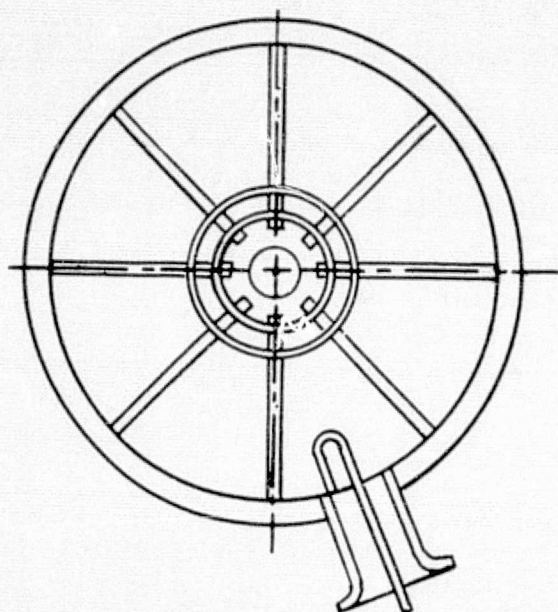
1.3.1 General Historical Background and Application of Amplitrons

Over the past 40 years a large number of different electron-tube approaches to the generation of microwave power have been developed. There are two general classes of tubes; linear beam tubes and crossed-field tubes. The second class, with which this report is concerned, can be subclassified in various ways. Two different subclasses with which we will be concerned are (1) injected-beam or continuous-cathode devices, and (2) oscillator or amplifier devices. The SPS requirement definitely calls for a device that behaves like an amplifier. There are crossed field amplifiers (CFA's) of both the injected beam and the continuous-cathode design. This report is concerned with a crossed field amplifier of the continuous cathode design quite frequently called the Amplitron (18, 19, 20, 21).

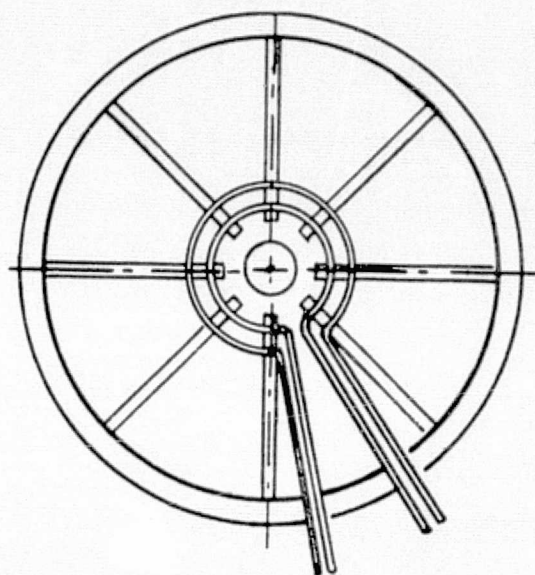
The device which is now called the Amplitron was invented in 1953. (18) It was derived from the magnetron and developed because of the desire to convert the conventional magnetron oscillator into an amplifier (18, 19). The Amplitron and the magnetron oscillator then have close similarities, with the major distinction being that the amplitron has a non-reentrant circuit which is matched at both ends to outside terminals while the magnetron has a reentrant circuit and only one output. This comparison is shown in Figure 1-14. The amplitron is also designed for use somewhere within the pass band of the slow wave circuit but away from the lower cutoff frequency while the magnetron is used at the lower cutoff of the slow wave circuit.

These differences not only endow the derived device with the properties of a broad band amplifier but also provide it with directional properties, that is, it has gain in one direction, but not the other. This is shown in Figure 1-15. The direction of gain can be changed by reversing the magnetic field. This reversal of direction of gain is a common property of all CFA's (crossed field amplifiers) and has led to a classification of tubes as forward wave CFA's or backward wave CFA's.

From a historical point of view, forward wave interaction promised the capability of operation over a wide frequency range without having to change the input voltage to the tube and thereby providing it with a capability called "instantaneous bandwidth". For this interaction a different kind of circuit than that used in the magnetron was preferred. Therefore two subcultures of continuous cathode CFA's developed which resulted in substantially different tubes because of the circuit differences. However, there is no reason why in principle the devices cannot be operated both ways if "instantaneous bandwidth" is not required. It was known, for example, that the original continuous cathode device (Amplitron) derived from the magnetron could be operated as both a forward wave and a backward wave device, (18, 19) although its backward wave mode was much superior for the application of the tube. It is also of interest that the "C" modification of the QKS1875 Amplitron which has a circuit structure



MAGNETRON



AMPLITRON

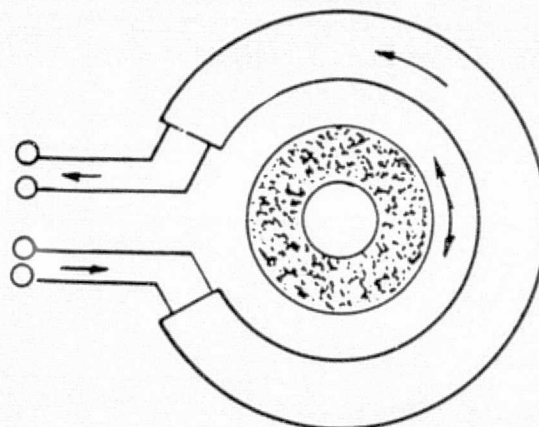
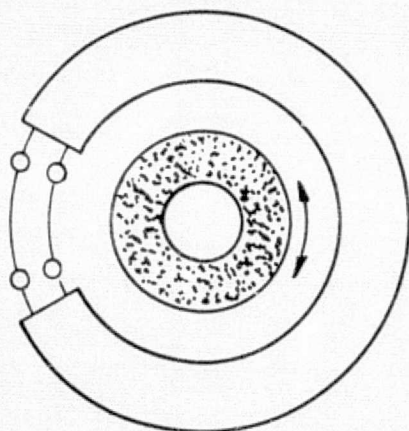
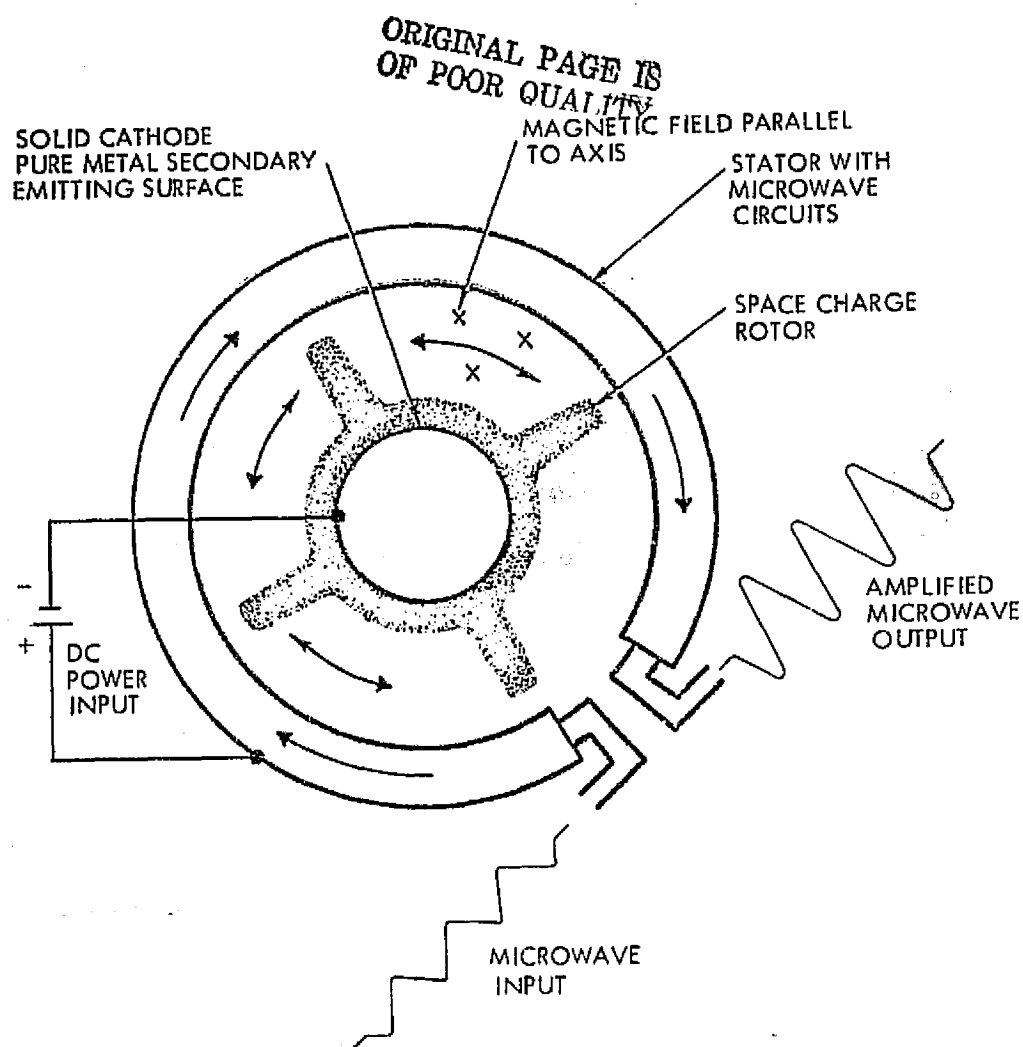


Figure 1-14. Diagram illustrating the basic differences of construction and operation between the Amplitron and the magnetron.



Although the details of Amplitron operation are complex, the principle is easily grasped by analogy to a 60-Hz alternator. In the Amplitron, there is a rotor consisting of spokes of space charge that induce high-frequency alternating current in a stator composed of a microwave circuit. The electric fields from the energy in the microwave circuit, in turn, exert a force against the spokes of space charge. The torque required to spin the rotor comes not from external mechanical torque, as in the 60-Hz alternator, but from the motion of charged particles in static electric and magnetic fields oriented at right angles to each other. Power is supplied to the rotor by the rate of loss of potential energy of the electrons as they move from the cathode to the anode within the spokes.

The Amplitron is placed into operation by applying the proper values of magnetic field and dc voltage between cathode and anode and then injecting an rf signal into the microwave input. This signal ionizes the minute amount of gas present in the tube and frees electrons which bombard the cathode and start the emission process. Build-up time to steady state is a few nanoseconds.

Figure 1-15. Principle of Operation of the Amplitron

identical to that of a common magnetron, operates in the forward wave mode as well as the backward wave mode. Most of the test information recorded in this report is for the forward wave mode.

Since its introduction in 1953 the Amplitron, (identified as the continuous-cathode, reentrant-beam, crossed field amplifier) has found wide application in pulsed radar applications where high efficiency, high power, and a modest frequency bandwidth is required. Figure 1-16 shows some but not all of the amplitron designs that have been developed by Raytheon Company for various applications. Nearly all of these designs are for backward wave interaction, and nearly all are for pulsed applications.

Although a significant amount of effort has gone into the successful development of CW amplitrons, these CW tubes have not been used to the extent of their pulsed counterparts. Part of the reason for this is that CW applications tend to be communication applications and in this area high gain linear beam devices are preferred to higher efficiency but lower gain crossed field amplifiers. One significant use of a CW Amplitron was in the Apollo program in which the QKS1300 CW Amplitron was used to boost the power level of high data rate transmission from the lunar lander to earth. This tube is the small tube in the foreground of Figure 1-16.

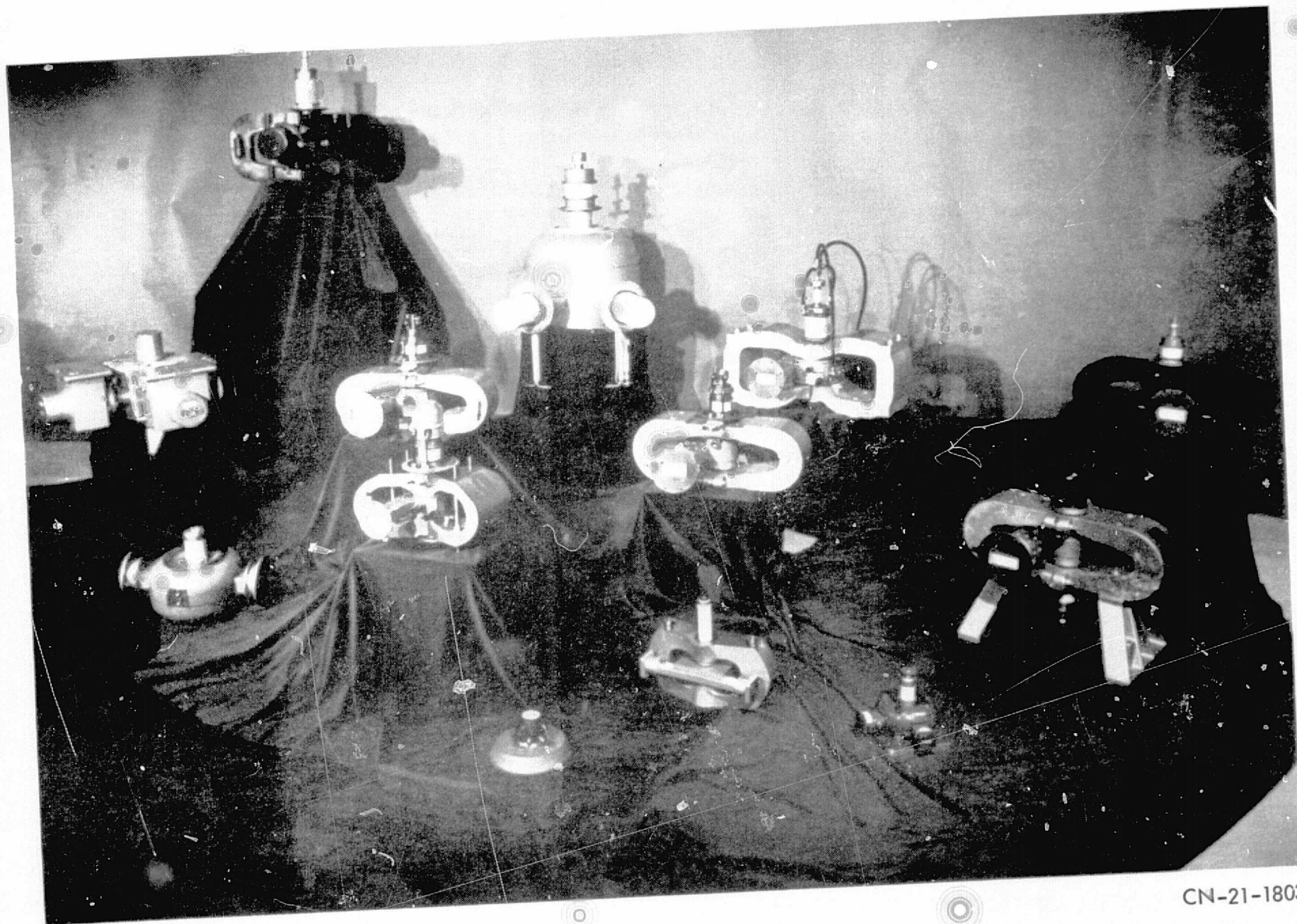
1.3.2 Background of CW Amplitron Development

Although there has been a steady development effort on pulsed amplitrons since the early development of the device, the development effort on CW amplitrons has been intermittent. Nevertheless, some of these developments have been of considerable significance and have had an influence upon pulsed amplitron design as well as upon subsequent CW amplitron development. They have had a particular significance to the development of the space-tube amplitron for the SPS.

The first significant CW development was the QK596 Amplitron developed in the 1956 to 1958 time period (22). Its chief significance to the current development was the extremely low level of noise achieved when it was used as a stabilized oscillator. It is described in considerable detail in the reference. An interesting feature of this tube is that it had a circuit which was external to the vacuum chamber. Only the cathode and anode electrodes were inside the vacuum chamber, making it possible to experiment with different external circuits. The tube had a thermionic cathode.

Its characteristics and noise performance features are summarized as follows

Anode voltage	600 volts, DC
Anode current	40 - 100 mA
Magnetic field	650 gauss



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Figure 1-16. A Collection of Reentrant-Beam Crossed-Field Amplifiers
Developed by Raytheon Company

EC power output	3 - 6 watts
Frequency	1110 - 1150 MHz (stabilized)
AM noise	95 dB below the carrier, over a 2.8 to 500 KHz band
FM noise	less than 3 Hz, rms, over a 2.8 ke to 500 KHz band
FM noise	less than 2 Hz, rms over 20 Hz to 5 KHz band

The close-in noise measurements are outstandingly low and should be the same if the device is used as an amplifier with either the input or output end well matched.

The second significant CW Amplitron development was the QK680, a 10 GHz tube developed in the 1958 to 1960 time frame. (23) This was a significant development which demonstrated the very high dissipation density that could be achieved with high velocity flow of coolant through small diameter tubes and the use of pole pieces that were kept at the same potential as the cathode to provide a sharp knee on the voltage current characteristic and make it possible to operate at high ratios of anode voltage to anode current. A brief summary of the characteristics of this tube follows:

Anode voltage	8 kilovolts
Anode current	50 mA to 1000 mA CW
Power output	375 watts to 5500 watts CW
Efficiency	62% maximum
Frequency	9.6 to 10.6 GHz
Noise	not measured

This tube had a directly heated tungsten rod for the cathode. The tube was started by heating the tungsten rod to thermionic emission temperature and then letting the tube run on secondary emission from back bombardment power.

The negative pole piece and high dissipation density features of this tube were then used on a CW tube (QK849) designed for a frequency of 3000 MHz and for a CW power of over 200 kilowatts. Two of these tubes were operated in cascade within one vacuum envelope (QKS1224) to produce 425 kilowatts of CW power output at a 10 db gain figure. The QK849 was operated with an overall efficiency of 76.7% at a power output of about 200 kilowatts. All tubes were designed with a secondary-emitting platinum surfaced cathode which was kept at room temperature by water cooling during operation. (24, 25)

The last CW Amplitron development and the one to have had the most immediate impact upon the current development was the QKS1532 Amplitron. The purpose of the QKS1532 Amplitron development was to have a lower power CW Amplitron that could serve as a driver for the higher power

tubes discussed in the previous paragraph. Its design was essentially scaled from the higher power QK849 Amplitron and it utilized a modified version of high velocity water cooling and a water-cooled, platinum-surfaced cathode. The scaled down version also represented an almost direct frequency scale of the QK680 so that data from both the QKS1532 and QK680 development are applicable to the current QKS1875 Amplitron development.

The greatest significance of the QKS1532 for the QKS1875 Amplitron development is that it employed a platinum cathode and was able to start and amplify well with a microwave drive of no more than one kilowatt. The CW microwave power output of this tube as a function of anode current for a drive level of one kilowatt is shown in Figure 1-17. It is noted that a gain of 10 dB was easily achieved with a power output of 10 kilowatts and that the minimum power noted was 2.8 kilowatts. The efficiency at that point was as good as at the higher power levels.

The QKS1875 has the same pitch or distance between vanes as the QKS1532 and therefore their V_0 voltage scales are the same.

1.3.3 Background of Efficiency in Amplitron and Magnetron Devices.

Because high efficiency is such an important consideration in reducing the amount of heat that the satellite solar power station must reject into space it is important to consider the background of information that exists on the efficiency of the Amplitron and the closely related magnetron. For both of these devices there are examples of very good efficiency, even though an all-out effort has never been made to optimize the efficiency in either one of these devices.

In both of these devices there is an efficiency that is derived from the relationship between the potential energy that an electron has before it leaves the cathode and the kinetic energy with which it hits the anode where it is collected. The difference between these two energies represents the transformation of potential energy into microwave energy. This electronic conversion efficiency is directly related to the ratio of the applied magnetic field to a design parameter of the tube called B_0 , and is given by the expression

$$\text{Electronic Efficiency} = \frac{\frac{2B}{B_0} - 2}{\frac{2B}{B_0} - 1} \quad (2)$$

This theoretical electronic efficiency is plotted in Figure 1-18 as a function of the B/B_0 . The performance of several outstanding tube developments from the efficiency point of view are also plotted in the same Figure. The 8684 magnetron (26) performance is especially interesting because it is a high

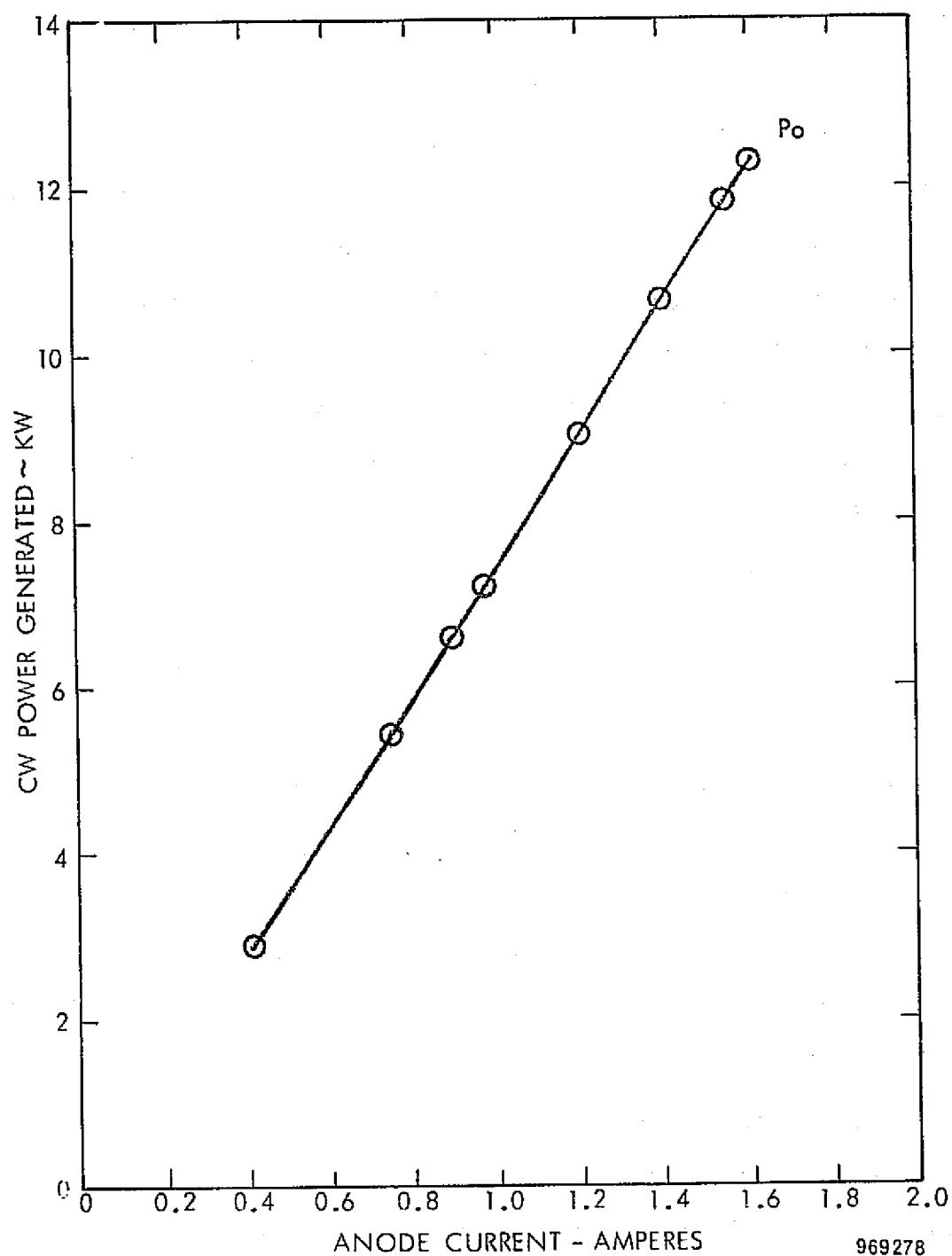


Figure 1-17. CW power output of the QKS1532 as function of anode current at an input drive level of one kilowatt.

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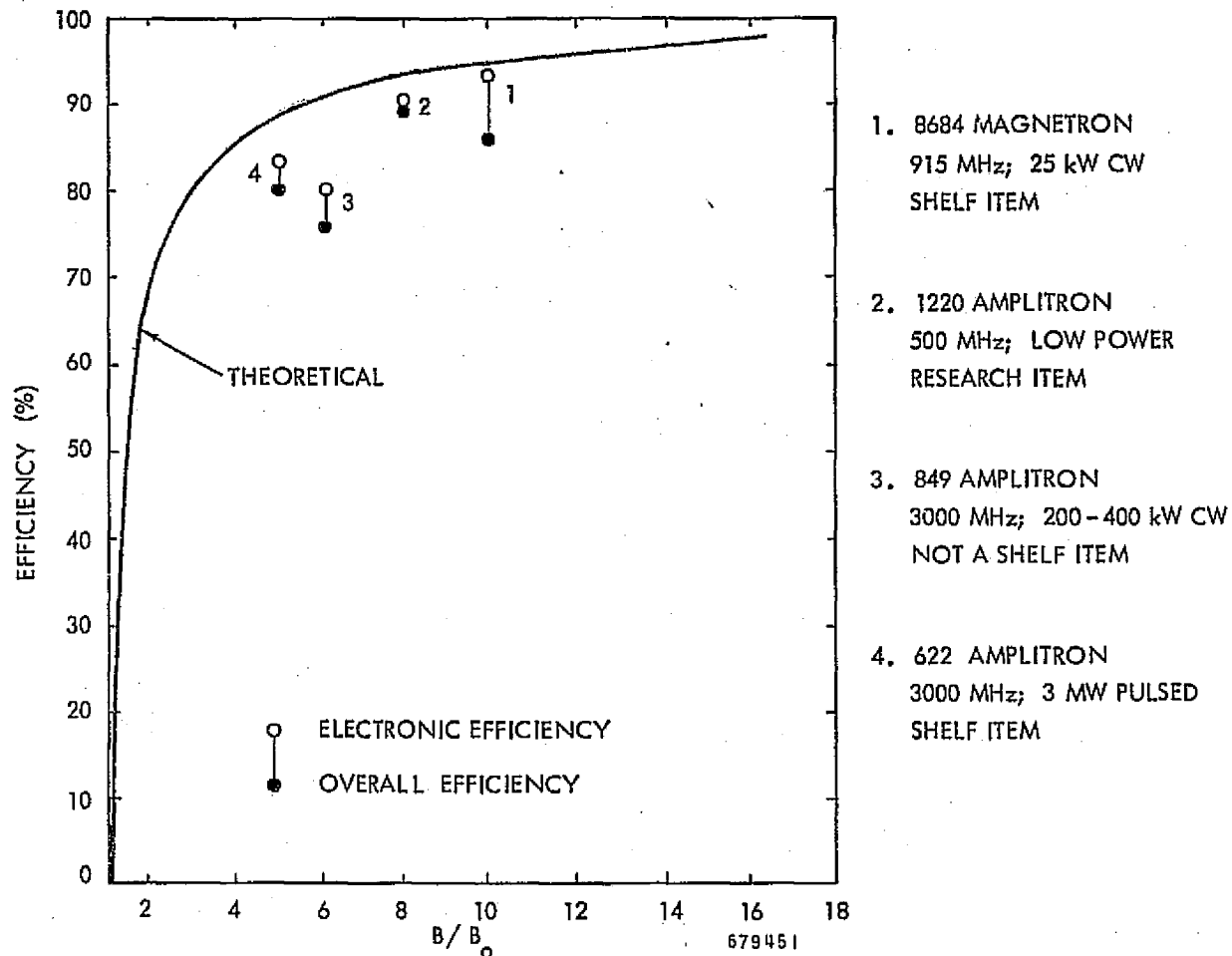


Figure 1-18. Theoretical and experimentally observed electronic efficiency of selected Amplitrons and magnetrons as a function of the B/B_0 ratio. Overall efficiency which is the product of electronic and circuit efficiency is also shown.

powered CW tube and it is a shelf item. Its electronic efficiency approaches the 93% given by the above formula very closely. The 8684 magnetron does not have a particularly high circuit efficiency and so its overall efficiency is about 85%. The QKS1220 Amplitron, (27) a pulsed tube, was operated at an indicated overall efficiency of 90%, at the higher values of B/B_0 but at a frequency of 500 MHz. Because the Amplitron has an inherent high circuit efficiency, even at 2.45 GHz, it would seem possible to obtain 90% or more overall efficiency from the Amplitron at that frequency when run at sufficiently high B/B_0 ratios and properly designed otherwise.

The equation for electronic efficiency given by (2) does not take into account the backbombardment power absorbed by the cathode, so for this reason the electronic efficiency will be somewhat lower. On the other hand it does not take account of vane shaping or other techniques to slow the electrons down from synchronous speed just before they reach the vane and which would increase the efficiency. With respect to cathode bombardment power, a cathode that supplies a substantial amount of primary emission or which has a high secondary emission ratio at low bombardment energies will require much less bombardment power to supply the necessary cathode emission. It is a matter of record (26) that the backbombardment power of the filament type cathode (filament) of the 8684 magnetron has less than 1% backbombardment power.

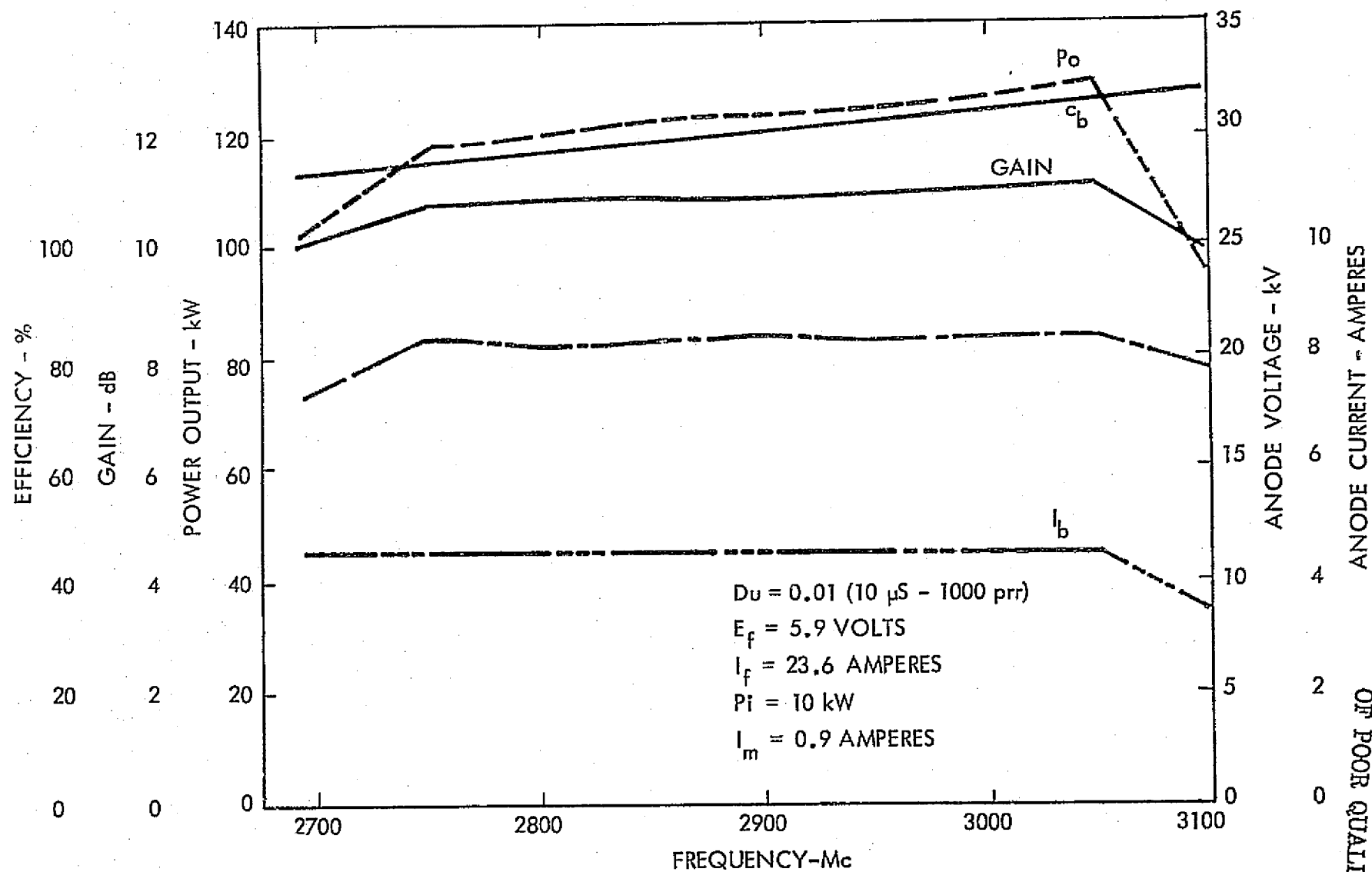
Figure 1-19 provides a set of high efficiency data on the QK727 Amplitron which is a high duty cycle pulsed amplitron whose level of output is about fifteen times that anticipated from the QKS1875. It is to be noted that the efficiency is slightly in excess of 80% over a wide range of frequencies.

1.3.4 The Initial Baseline Design of the Space Amplitron

The initial baseline design of the space amplitron is defined as that design which had been arrived at before the inception of the work effort on phase I of the development and which this report covers. The design of the first QKS1875 Amplitron that is described in Section 2.3 was based upon this baseline design for the space tube although important changes had to be made to accommodate the enclosure with a vacuum envelope, and to match the internal circuit to the input and output in a manner to handle the microwave power level while not interfering with the flow of heat to an external radiator.

The initial baseline design had been arrived at through a series of previous studies that had reviewed the problem of disposing of waste heat into space (10, 11, 28) and that had attempted to optimize the electrical size of the tube to accommodate this requirement.* It had been concluded that the usual cooling method of running water or other coolant through the vane tips of the anode would not be acceptable in this type of application and that a solid vane construction with conduction of heat to the back wall would be necessary. This kind of construction which closely resembles that in a conventional magnetron is a new departure in the design of amplitrons. At the back wall point

* Much of the work on selecting an initial baseline design was done by George Mac Master and Kenneth Dudley under both Raytheon support and NASA support. See reference 28.



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55 Figure 1-19. Performance Characteristics of the QK727. Performance data indicates an efficiency of over 80% over a 10% frequency range.

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there is a choice between using heat pipes to transmit the heat to a large surface or to use a light-weight highly conducting material such as pyrolytic graphite to passively conduct and radiate the heat. Because of the high probability that unprotected heat pipes would be subject to puncture by micrometeoroids it was decided to use purely passive radiation cooling.

Because of the desire for very long life as well as the desirability of eliminating a heater supply for a thermionic cathode which would have to be isolated from ground it was attractive to use a pure metal secondary emitting cathode which would have extremely long life from which emission could be initiated by the normal microwave drive power providing that drive level was in the range of one kilowatt. This suggested arrangement led to the concept of cascading of tubes that was discussed in section 1.2.4. A pure metal platinum cathode was therefore used in the base line design, but because of the back bombardment power and the relatively low operating temperature of the cathode, it would be necessary to supply a heat radiator for the cathode as well as the anode.

The initial baseline design of the space tube is shown in Figures 1-20, 1-21, and 1-22. Figure 1-22 is a photograph of a model of the tube and the waveguide into which it is inserted. This concept should be compared with the later concept shown in Figure 1-4. The designs should not be taken literally in all respects. For example, the pole piece moving arrangement in Figure 1-20 has not been carried out in detail. On the other hand the first slow wave circuit to be constructed approximated the one shown in Figure 1-20 very closely. The number of vanes and their pitch was not changed in the QKS1875 Amplitron design.

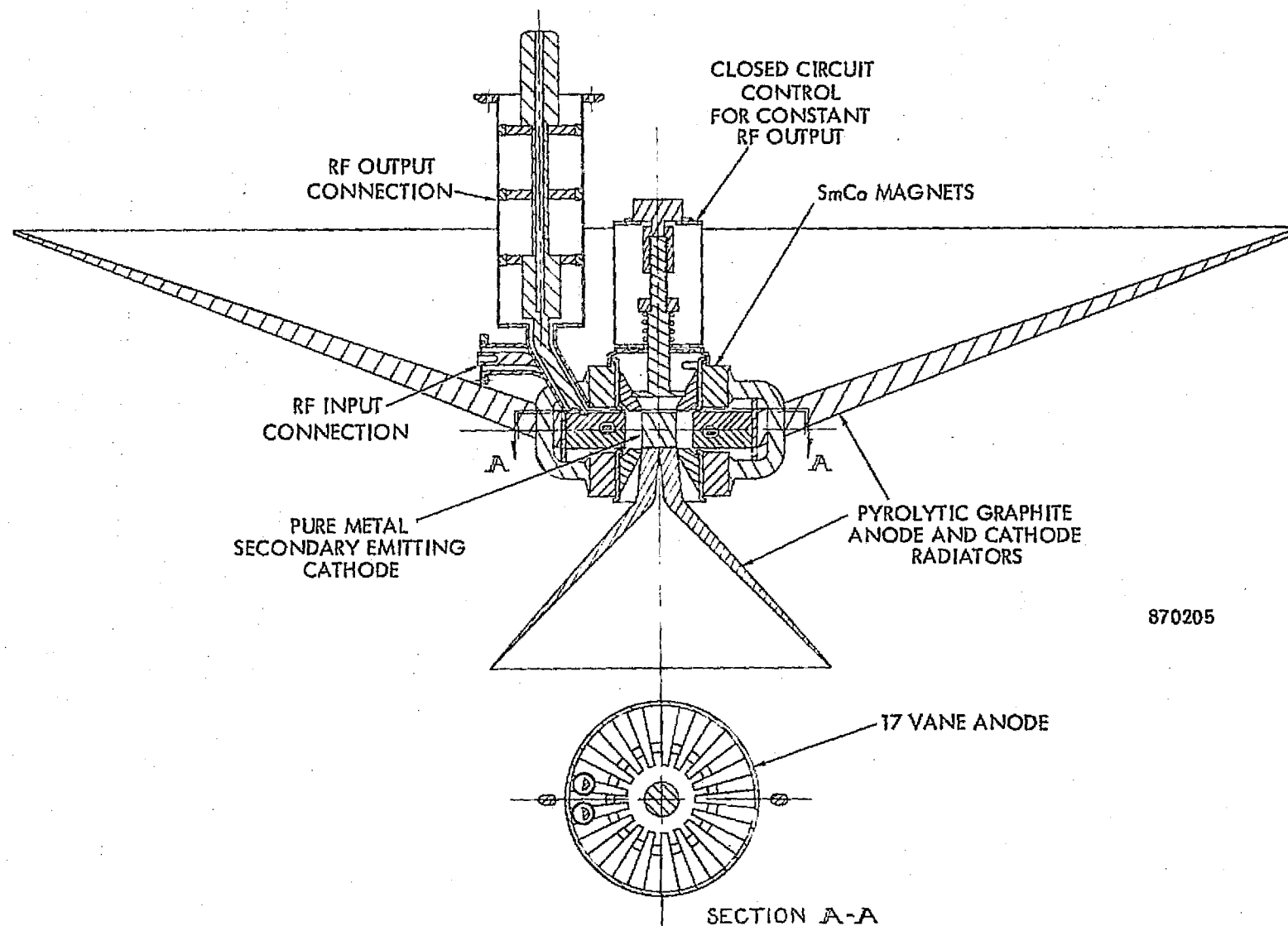
The baseline design had been made for a frequency of 2.45 GHz after a number of investigations had indicated that this frequency region near 2.45 GHz represented a good compromise between the severe attenuation that would result in the earth's atmosphere under certain meteorological conditions at higher frequencies and the larger sizes of the transmitting and receiving antenna required at the lower frequencies. From the viewpoint of the DC to RF and RF to DC converters 2.45 GHz represented a frequency where the known efficiency of the devices was high. In Section 4 of reference 28, a number of studies were made of the weight, efficiency, and cost of the tube as a function of frequency which indicated a frequency in this region was optimal. The exact frequency of 2.45 GHz was chosen because it is at the middle of the ISM band where there is no potential interference with the services and equipment already in that band.

With the frequency selected there had remained in the design selection process the matter of the electrical and physical size of the tube. The factors that impact the electrical size of the tube are given in Figure 1-23. They have been studied quantitatively in reference 28. An overriding factor in the size of the tube is the specific mass of the tube, as measured by the ratio of the mass of the tube to the electrical power output because of the high cost of transporting mass into space. This ratio is very critically dependent upon the efficiency because of the substantial amount of mass that is required to conduct and radiate the waste heat. The base line design has a passive radiator of near

* J.W. Leach and R.L. Cox. "Flexible Deployable-Retractable Space Radiators"

Section on Micrometeoroids AIAA Paper #1896, 12th. Thermophysics Conference, June 27-29, 1977 Albuquerque, N.M.

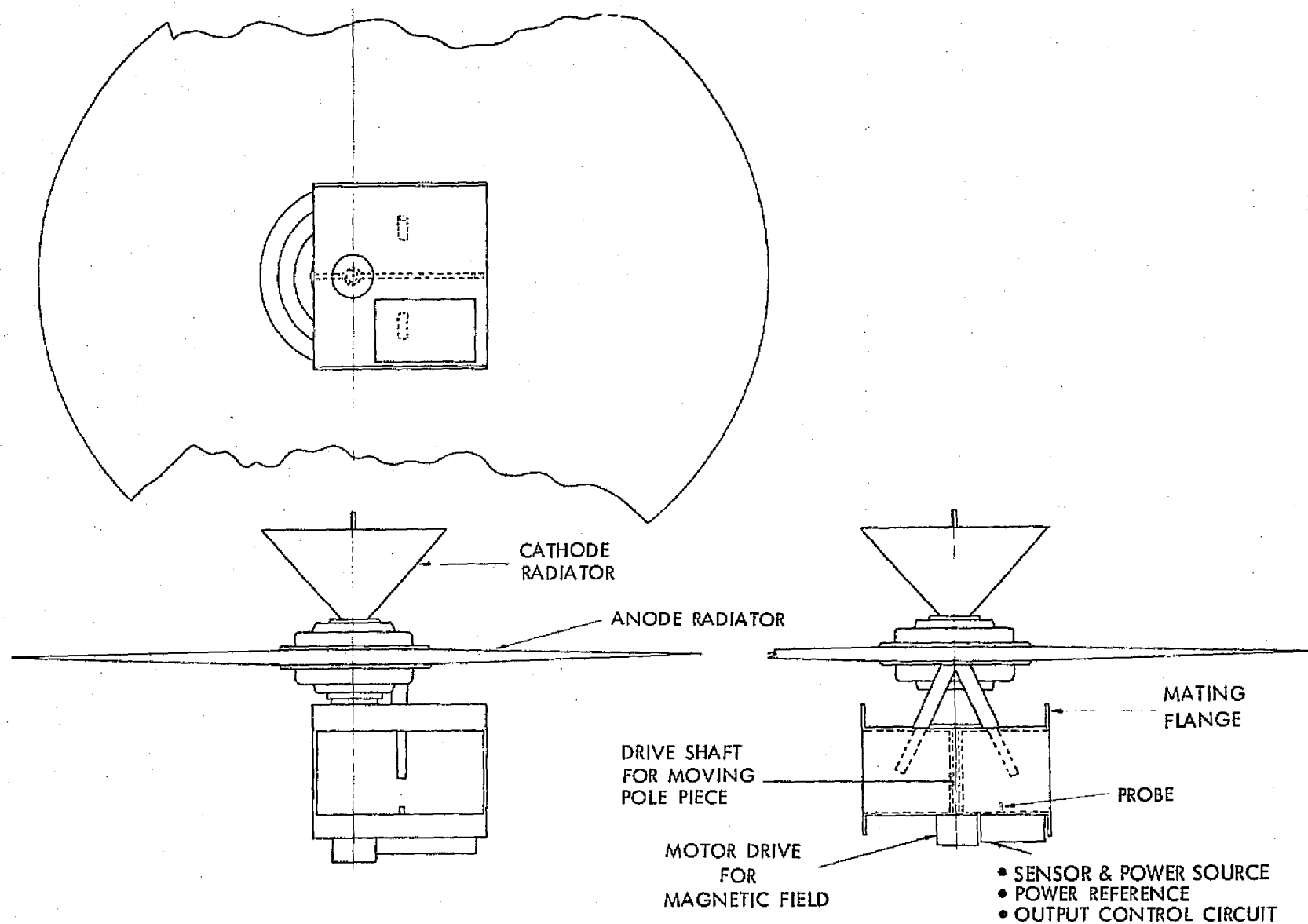
CROSS SECTION DRAWING OF ORIGINAL TUBE



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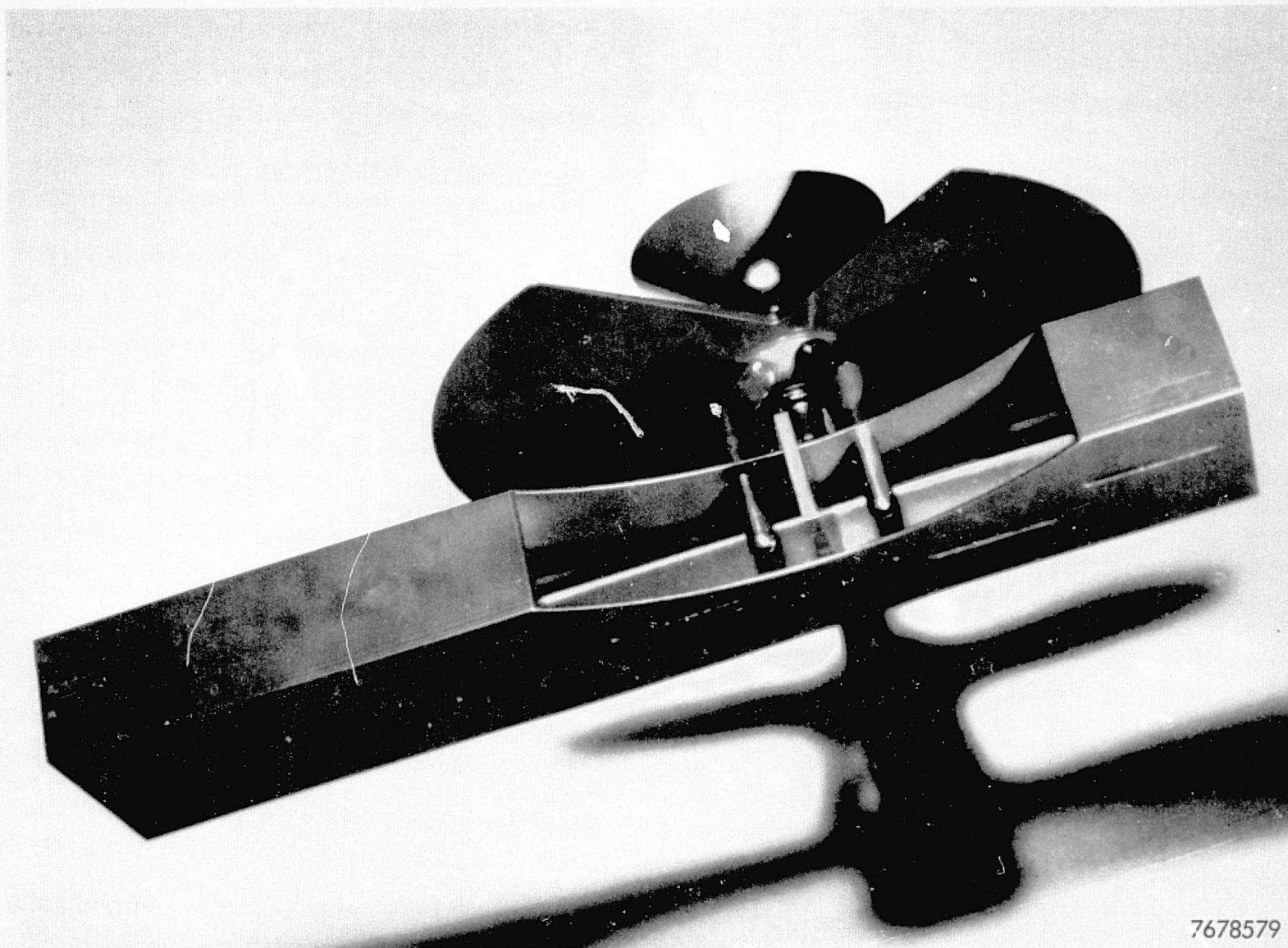
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Figure 1-20. Baseline design of the SPS Amplitron that was established prior to undertaking the work effort covered by this report. The anode and cathode configuration and dimensions were retained in the baseline design for the QKS1875 Amplitron constructed under this work effort. Water cooling of anode and cathode and a ceramic envelope around the vacuum were basic departures from the space-tube design. The input and output coupling arrangements have also been substantially reworked.



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Figure 1-21. Outline drawing showing the proposed integration of the baseline design of Figure 1-20 with a waveguide output. Also shown are an output sensor probe and an arrangement for moving the pole piece to change the magnetic field. The necessary solid state components are mounted on the outboard side of the waveguide which is expected to be cool enough to permit the use of solid-state components made from gallium arsenide.



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39 Figure 1-22. Photograph of a mechanical mockup of the configuration illustrated in Figure 1-21. For the Amplitron waveguide interface a substantial change in the configuration of the input and output connections to the Amplitron from that shown in Figure 1-20 was necessary to establish the Amplitron waveguide interface shown in Figures 1-22 and 1-21.

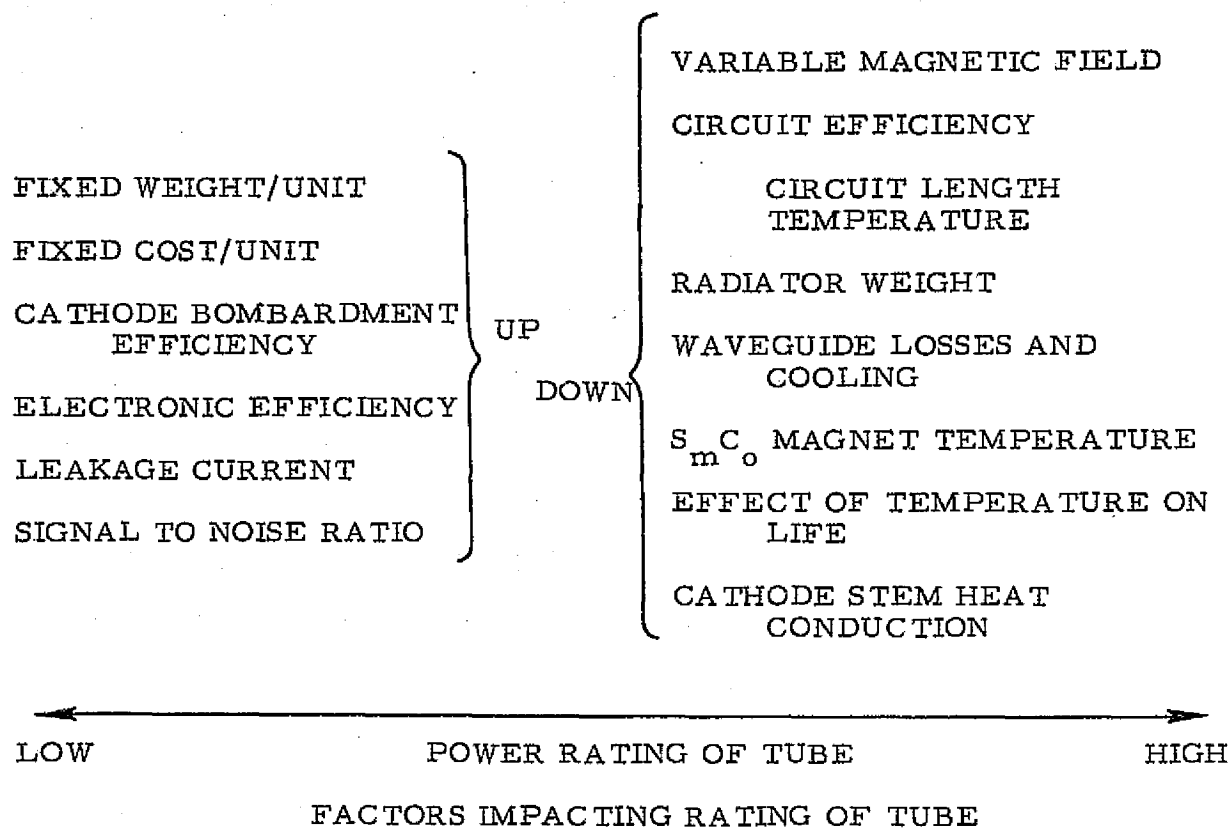


Figure 1-23. Factors impacting the power rating of the space Amplitron.

optimum form, a circular geometry with a wedge-shaped cross section. The mass of this radiator increases approximately as the 2.5 power of the heat that it radiates.

It can therefore be shown that the mass of the radiator is given by:

$$\text{mass of radiator} = K \left(\frac{1-\eta}{\eta} P_o \right)^{2.5} \quad (3)$$

where η is the efficiency and P_o the microwave power output.

It is observed that the mass of the radiator is highly dependent upon the inefficiency of the tube. The mass of the radiator for a 90% efficient tube will be only 13% that for an 80% efficient tube; that for a 93% efficient tube only 12% that of an 85% efficient tube.

If the radiator were the only mass in the tube, then the power rating of the tube should be as small as possible because it is seen that the ratio of the mass of the tube to its power output, varies as the 1.5 power of the power output.

Of course there are elements in the tube such as the pole moving mechanism which may be relatively independent of power output and others such as the magnet weight and anode weight that are more nearly proportional to power output which may prevent the size of the tube to obtain minimum specific weight from becoming vanishingly small. Nevertheless, in the long run very high efficiencies are deemed to be possible, and the weight of the radiator is such a dominant factor in the design that the optimum size of the tube from a specific weight point of view tends to become quite small.

But then the question to be asked by those with experience in the design and operation of such tubes is whether the efficiency will hold up at such low power levels. This question arises because of the tendency of electrons to leak out of the interaction area at very low values of operating current and reduce the operating efficiency or to prevent operation entirely. Fortunately there have been demonstrated ways to cope with this problem by operating the pole pieces at cathode potential and in properly shaping the magnetic field, as discussed in Section 1.3.2.

Another practical reason for not operating at extremely low power levels is the desire to start the tube with the injection of microwave power. Prior experience had indicated that an input drive level of one kilowatt would be a reasonable value.

All of these factors - the weight of the radiator in the space tube, the efficiency, the minimum expected power level to start the tube, and the loss in efficiency caused by leakage current from the interaction area were

all taken into consideration in arriving at a set of objective specifications for the space tube which would also become the objective electrical specifications for the amplatron design for the first phase of the space tube development.

The Resulting Objective Electrical Specifications are:

Efficiency	85% minimum
RF Power added	5 - 8 kilowatts
Gain	7 dB
RF load	operable into both dual-mode horn and slotted waveguide as well as matched waveguide water load.
Cathode Surface	pure metal (non-oxide surface)
Frequency	2.45 GHz
Cooling	design to be compatible with eventual conversion to cooling with passive devices i.e., cooling without additional expenditure of energy.

The breakdown of the mass of the space tube base line design is given in terms of weight as

Anode	108 grams
Anode Radiator	1000
Cathode	9
Cathode Radiator	71
Magnet	260
Poles	100
Input and Output	40
Motor and Drive	30
	1618 grams = 3.56 lbs.
Specific Weight	0.33 grams/watt

1.3.5 Suggested Three Phase Program for Development of Space Tube

The tube development with which this report is concerned was considered to be the first of a three phase development to produce an amplatron that will be tested in a vacuum environment and used in space. As such, the design of the tube for the first phase must logically lead into and be adaptable to the succeeding stages of development.

The development content of the various stages as well as the uses of the tubes produced by these stages is shown in Figure 1-24.

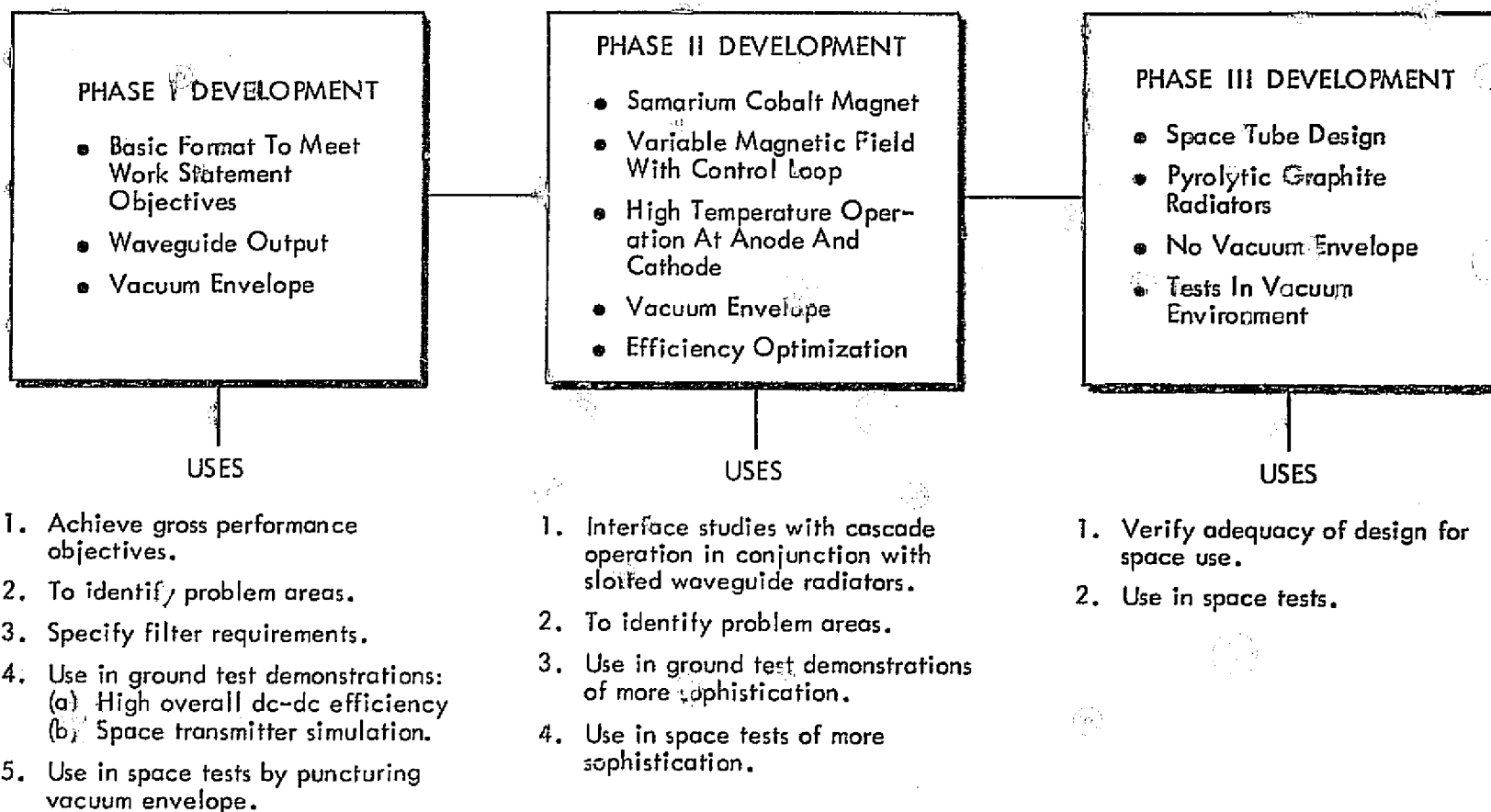


Figure 1-24. Proposed phased development of Amplatron for SPS application.

It should be understood that the complete development of the tube could be broken down into more than three stages. However, the content of the initially proposed three stages of development is indicative of the total content of any development program to produce the space tube.

2.0 DESIGN, DEVELOPMENT AND TEST OF THE AMPLITRON

2.1 Introduction

The QKS1875 Amplitron is defined as the tube designed to meet the performance objectives of the contract as given in Section 1.3.4 while still being consistent with the longer range objective of conversion to a space tube capable of meeting the requirements for a microwave generator in the SPS.

The material covered in this section represents nearly all the work effort under the contract. The design of the space tube, with a few important exceptions, had already been well delineated prior to the work effort under this contract and is discussed in Section 1.2 and 1.3 of this report.

Section 2.1 of this portion of the report discusses a number of critical issues involving the base line design of the tube and the arranging for its testing that were necessarily resolved early in the work effort.

These involved: (1) mechanically rugged and electrically broad band connections of the input and output to the slow wave structure that did not compromise the flow of heat to the external radiator (2) a high degree of magnetic field symmetry (3) an adequate test facility for noise and efficiency measurements, and (4) a cost effective design for construction, repair, and design modification.

Section 2.3 deals with the mechanical design and assembly of the tube.

Section 2.4 deals with some of the essential crossed-field tube electron dynamics and circuit theory essential to the design of the QKS1875.

Section 2.5 reports upon the experimental results and test data and their agreement with theory. The measurements include signal to noise ratio, operating efficiency and circuit efficiency, adherence of operating voltage to predicted voltage, and limited gain and power output measurements. The high value of signal to noise ratio is believed to be especially significant.

Section 2.6 deals with modifications of the baseline design, the purposes of the modifications, and the degree of success of such modifications.

Section 2.7 is a separate section reflecting the importance of understanding the reasons for the comparatively low gain and maximum power of the tube and for the lower efficiency than anticipated.

2.2 Critical Issues on the Development Program for the QKS1875

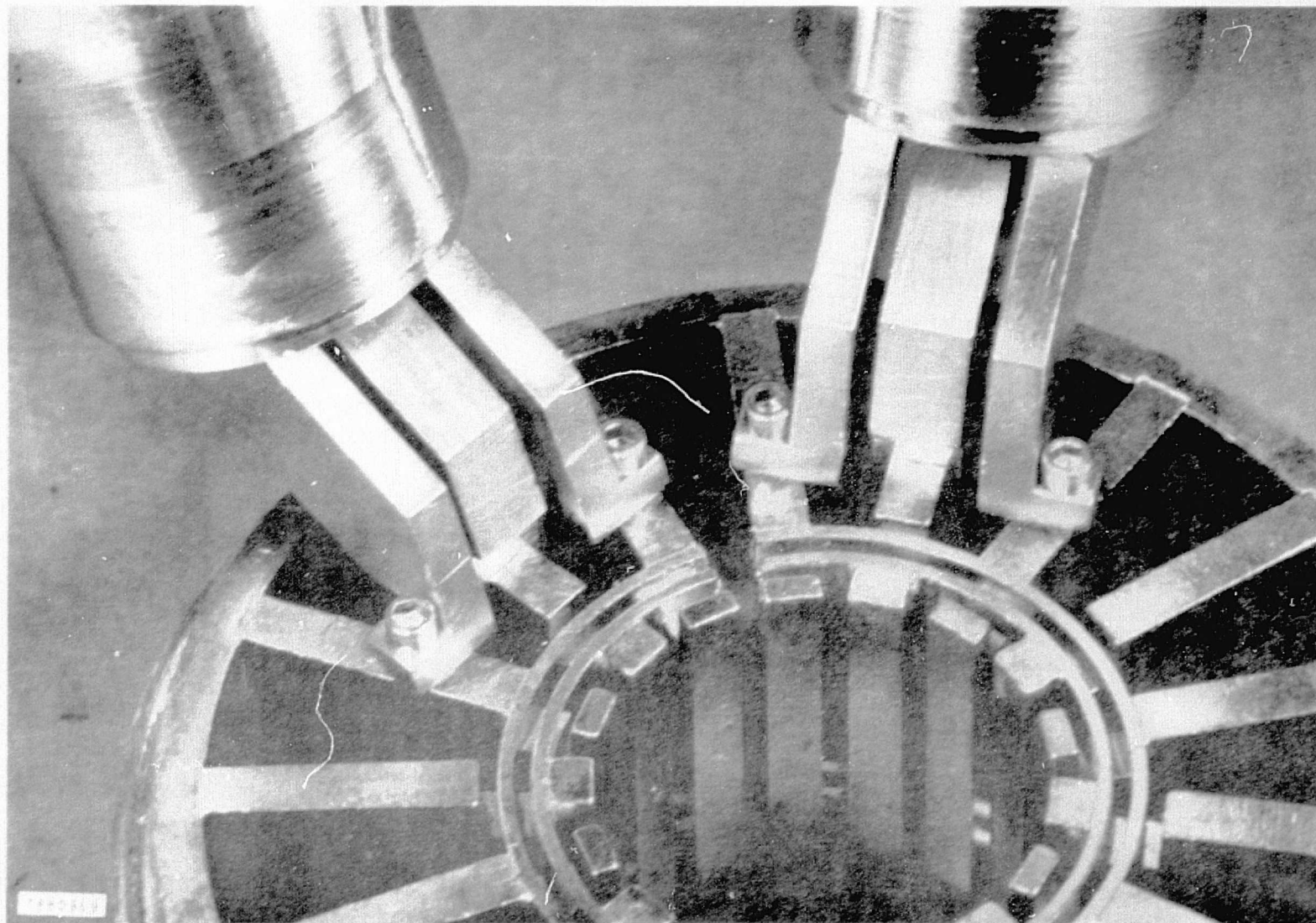
There were four issues that were judged to be most critical with respect to meeting the objectives of the technology development. These critical issues are listed below and will be discussed in this section.

- 2.2.1 The design of the input and output and the associated method of impedance matching to the slow wave circuit.
- 2.2.2 Magnetic Field Symmetry
- 2.2.3 An adequate test facility for noise measurements and efficiency measurements.
- 2.2.4 A cost-effective design for construction, repair, and for obtaining a broad range of test data.
- 2.2.1 The Design of the Input and Output and the Associated Method of Impedance Matching to the Slow Wave Circuit.

The need to conduct the heat from the vane tips where most of it is generated to the back wall of the tube and then into a symmetrical radiator has necessitated (1) the use of a solid vane design in a construction format similar to that used in most magnetrons (2) the connection of the input and output transmission lines to the top of the vanes to obtain a suitably massive structure for low rf losses and for good heat conduction.

The approach to meeting these requirements is shown in Figure 2-1. The vane and strap configuration shown there is common to magnetrons but unique to amplitrons. The connection of the input and output to the slow wave structure is believed to be a unique form of coupling to either magnetrons or amplitrons. It was arrived at after several other approaches had been tried and found to be unsatisfactory. The design shown in Figure 2-1 has many desirable features including massiveness and a broad band matching capability but it is possible that it may be contributory to the poor field patterns that are believed to be associated with the poor gain of the tube and the lower efficiency than expected. More effort in investigating the relationship between the two is necessary. This subject is discussed in greater detail in Section 2.7.

The coupling of the output circuit to the slow wave circuit is in the form of a balanced coupling. This makes it possible to obtain a much higher value of resistance when looking into the slow wave circuit and eliminates the high value of series inductance that occurs with an unbalanced coupling to the top of one vane. With the unbalanced coupling to the top of the vane there is always a high ratio of inductive reactance to resistance when looking into the tube from the outside. This high ratio makes it difficult to obtain a broad band match.



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Figure 2-1. Construction arrangement for an adequate electrical, mechanical, and thermal contact of the input and output transmission lines to the slow wave circuit of the QKS1875 Amplitron. Arrangement permits uninterrupted heat flow from the vane tips to the circular heat radiator around the tube as well as providing good conduction cooling of the input and output transmission lines and minimization of the skin losses because of the large surface areas involved. "Balanced coupling" arrangement also allows broad band matching between input and output and slow wave network.

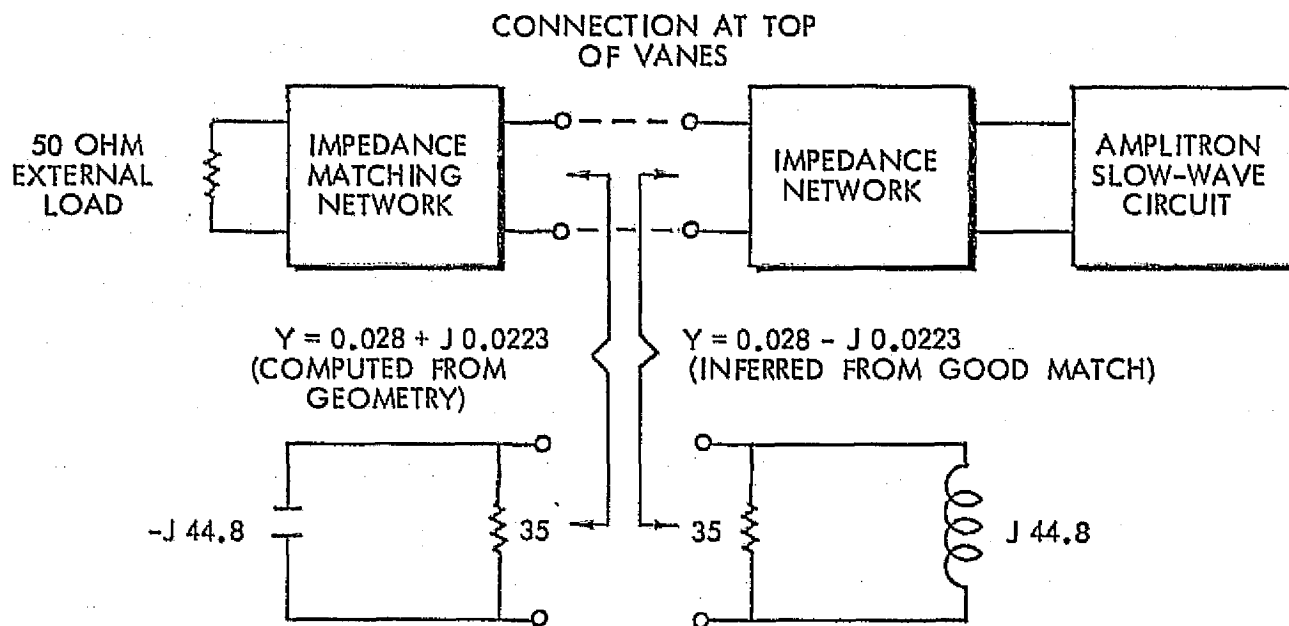
Although the coupling of the structures at the top of the vanes is a balanced coupling, the power in the QKS1875 must flow outward to an external load through a coaxial line which is an unbalanced structure. This would normally call for some kind of a balun structure so that the connection to the vanes is truly electrically balanced with respect to ground potential which is taken to be the surface at the vane roots. A balun is normally accomplished at microwave frequencies with the use of a quarter wave choke, but it was not done in the QKS1875 design because of the mechanical complexity of integrating it into vacuum envelope. This would not be the situation in the space tube. It was, however, possible to make cold tests employing such chokes and they seemed to make little difference either in the match obtained or in the field patterns in the interaction area.

The arrangement shown in Figure 2-1 does not eliminate all reactive component because of the inductance represented by the back of the cavities formed by the vanes and the back wall. However this residual inductive reactance is about equal in magnitude to the resistive component and is relatively easy to match out over an acceptable range of frequencies.

These values of impedance or admittance at the point of contact at the top of the vanes cannot be obtained by direct measurements. To make proper measurements in the direction of the slow wave network, the slow wave network would need to be terminated in its own characteristic impedance to permit such measurements. Looking in the direction of the output there is the difficulty of coupling into a balanced network for measurement purposes. Nor is it practical to make a computation of the impedance because of the difficulty of electrically modeling the complex geometries involved.

It was possible, however, to build a special impedance transformer whose parameters could be electrically modelled and then proceed to trim the transformer until a good match was obtained to the internal structure by taking a succession of "Weissfloch" or "S-curve" measurements. (29, 30) Then the output impedance was calculated by using the electrical model. From the good match that was obtained, it was then assumed that the impedance or admittance looking into the tube at the point of connection of the impedance transformer was the conjugate impedance or admittance.

This procedure, logic, and the results are indicated in Figure 2-2. It is of interest that the inductive susceptance looking into the slow wave structure at the tops of the vanes is very close to the computed value of the susceptance of the cavity formed by the portion of the vanes between the point of attachment and the back wall. However, it should not be inferred that the conductance part of the admittance is the characteristic admittance of the slow wave network, but rather the admittance of the network as transformed by the geometry between the point of attachment and the straps from which the characteristic admittance of the network is usually viewed.



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Figure 2-2. Measurement procedure for indirectly arriving at the input admittance to the internal structure at the point of connection of the input and output conductors to the top of the vanes as shown in Figure 2-1.

An expression for the computed value of the mid-series characteristic impedance of the slow wave structure is given in Section 2.4. At 2450 MHz the impedance is 73 ohms for the 0.400 in. long anode and 77 ohms for the 0.700 in. long anode. The higher impedance for the longer anode results from the fact that the lower cutoff frequency is at 2250 MHz rather than 2150 MHz. The characteristic impedance is a sensitive function of the ratio of 2450 MHz to the lower cutoff frequency as shown in Section 2.5.

It should be pointed out that the special termination that was used for the admittance calculations given in Figure 2-2 could not be used in the mechanical design of the tube because of its 90 degree orientation to the vanes which made it occupy much of the same space that would be normally occupied by the pole pieces.

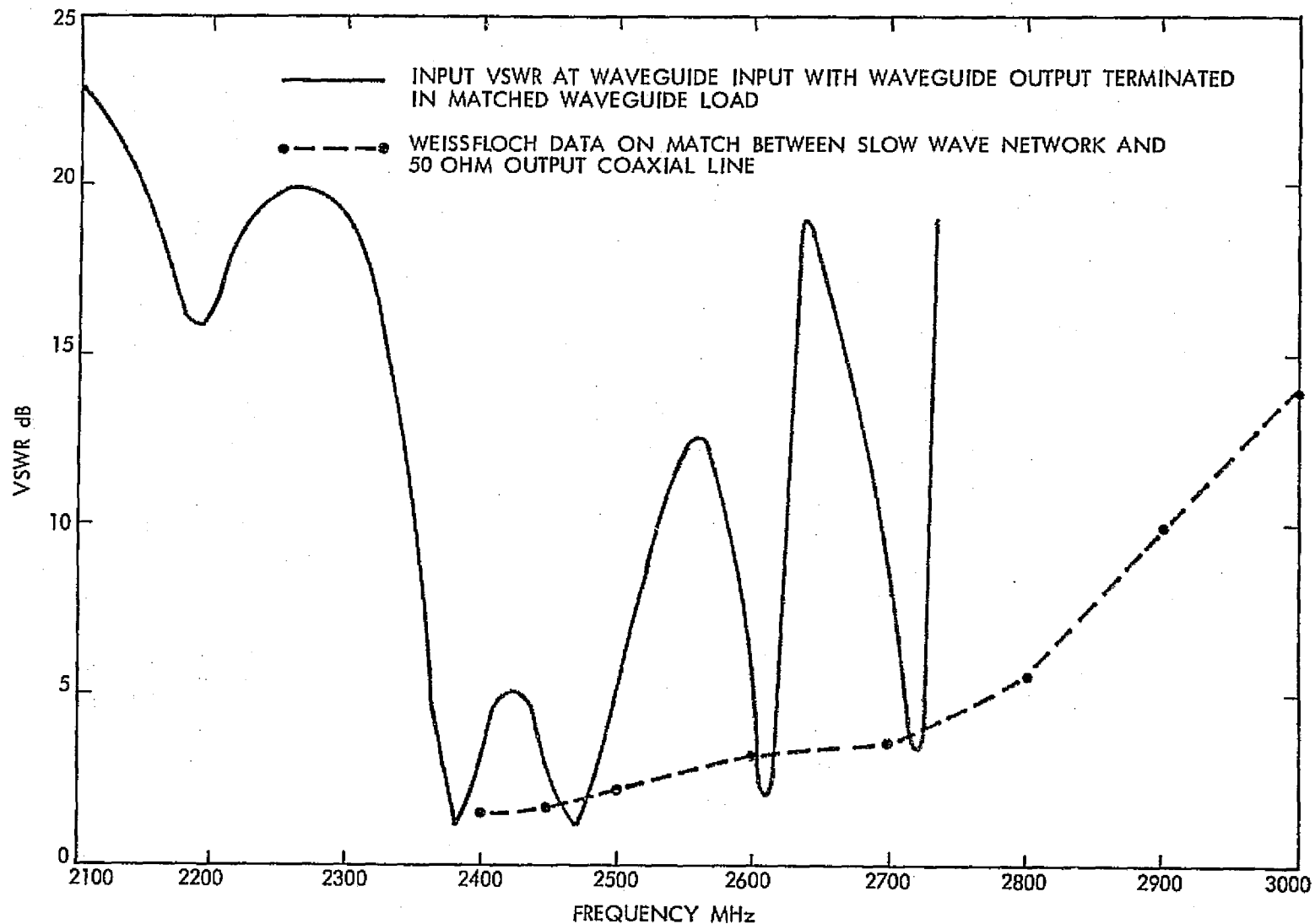
A good match may be obtained to the slow wave network with the arrangement shown in Figure 2-1. The match that was obtained for the QKS1875D design is shown in Figure 2-3. The amount of power reflected in the 2400 to 2500 MHz region is seen to be less than 2%.

The match data shown in Figure 2-3 was obtained from Weissfloch or S-curve data (29, 30). The outboard end of the impedance matching section of the output connection was attached to a 50 ohm transmission line with a moveable probe standing wave detector to obtain the Weissfloch data.

In conclusion, it is pointed out that the mechanically complex impedance matching network shown in Figure 2-1 was arrived at only after the investment of considerable effort on other approaches that did not yield satisfactory results. The present arrangement has these desirable and undesirable features.

Desirable Features:

- Both the center conductor and outer conductor are very rugged and capable of handling the microwave power levels anticipated for them.
- The balanced coupling raises the ratio of conductance to susceptance at the point of connection to the level where a relatively broadband match can be made.
- The connection is such that the output and input transmission lines avoid both the magnetic circuit for the tube and the heat conduction circuit from the vane tips to the external heat radiator.
- The geometry is such that the capacitive susceptance that is needed for the match is obtained without excessively close spacing. The closest spacing is about one millimeter.



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Figure 2-3. (a) Match of 50 ohm input and output transmission lines to slow wave structure as provided by Weissfloch measurement techniques, and (b) input standing wave ratio of tube with coaxial-to-waveguide fittings attached as shown in Figure 2-13. Waveguide of output transition is matched into broadband waveguide termination.

Undesirable features:

- It is difficult to obtain an adequate equivalent circuit because of the involvement of two cavities rather than one.
- In its present form, the coupling and the impedance matching format may be contributory to the poor field pattern in the tube.

2.2.2 Magnetic Field Symmetry

It is highly desirable to have magnetic field symmetry in a crossed field device because dissymmetry may be associated with less than ideal efficiency and perhaps with noise as well. It is known that a "C" shaped magnet introduces considerable circumferential dissymmetry into the magnetic field while an "E" shaped magnet greatly reduces such distortion. However, even an "E" shaped magnet produces some circumferential dissymmetry.

For the space tube design a completely symmetrical field may be provided by a symmetrical permanent magnet. However, in the first phase development with which we are now concerned it was desired to have a magnetic field provided with an electromagnet in order to be able to continuously vary the magnetic field.

In the development of crossed field tubes the electromagnet is almost always of the "C" shape or "E" shape. Therefore the provision of a means to apply a circumferentially symmetrical field with an electromagnet became an initial issue in both the testing equipment and the design of the tube. The problem was solved by using a large torroidal type electromagnet that is commonly used for the 8684 25kw cw magnetron at 915 MHz to supply the magnetomotive force and the use of both external pole pieces and internal pole pieces designed so that the field in the interaction area would be both circumferentially and axially symmetrical.

The first design of the complete magnetic circuit including internal pole pieces is shown in Figure 2-4. The geometry of this arrangement allows the use of input and output pipes that are joined to the tube with 45 degree angle and this angle greatly simplifies the mechanical design of the impedance matching network. However, the magnetic circuit did not provide an axially symmetrical field, and the departure from it was felt to be sufficiently significant to redesign the magnetic circuit.

The redesigned magnetic circuit is shown in Figure 2-5. In order for the tube design to be compatible with placing the interaction area of the tube in the center of the solenoid it was necessary to bring the input and output pipe connections into the tube at a considerably steeper angle. The external pole piece design shown in Figure 2-5 is the one that has been used in all of our test activity. There has been some slight modification of the internal pole piece design from that shown in the figure. Figure 2-b shows a plot of the lines of magnetic force for the geometry of 2-5a. The plot was obtained by means of the special computer program for magnetic circuits.

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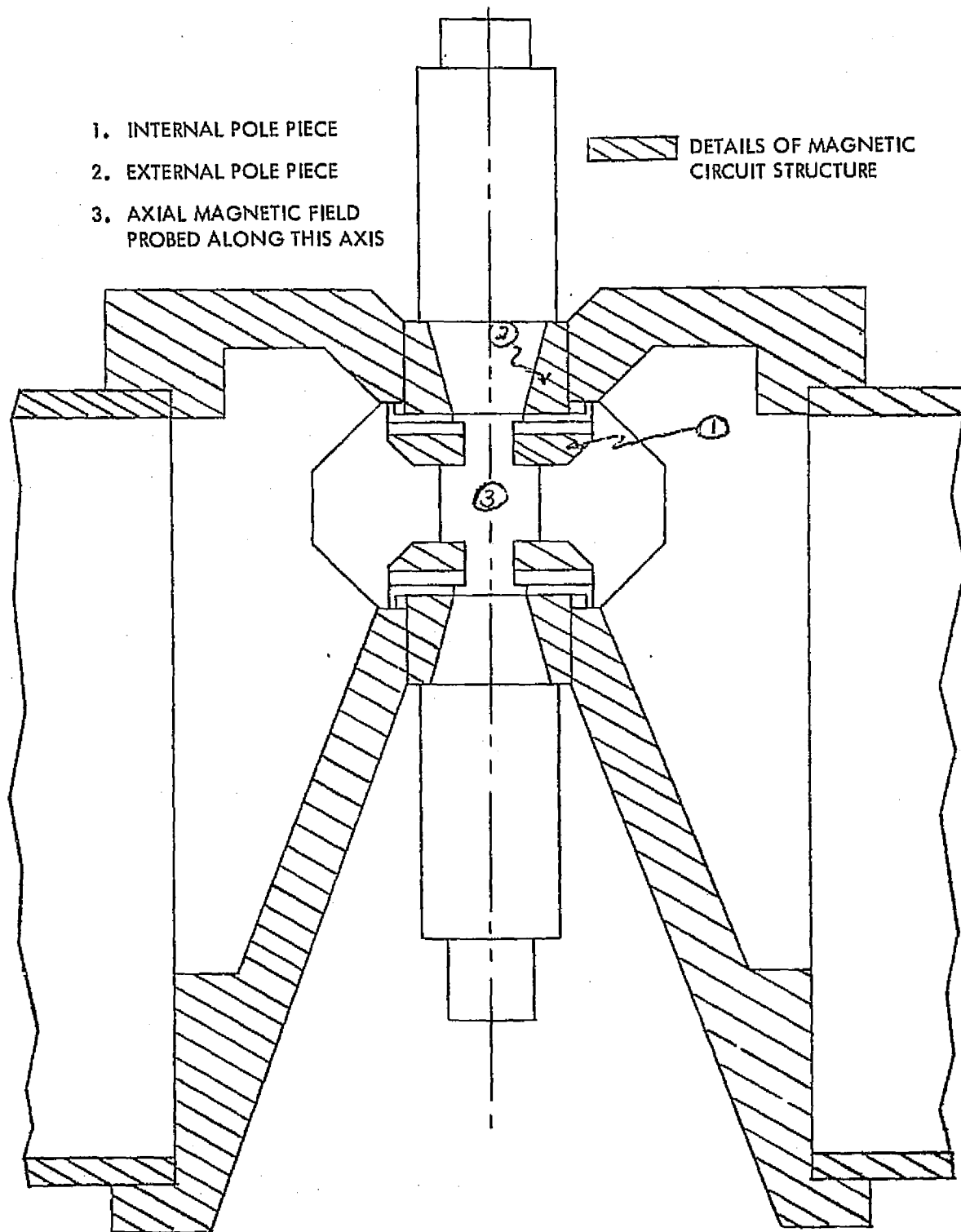


Figure 2-4. Original magnetic circuit indicating the portions internal to the tube and the portions external to the tube. Magnetomotive force is provided by a solenoid with a 5 inch inner diameter. Measurements of magnetic field indicated a substantial amount of axial dissymmetry.

REVISED MAGNETIC CIRCUIT

- 1. INTERNAL POLE PIECE
- 2. EXTERNAL POLE PIECE

DETAILS OF MAGNETIC
CIRCUIT STRUCTURE

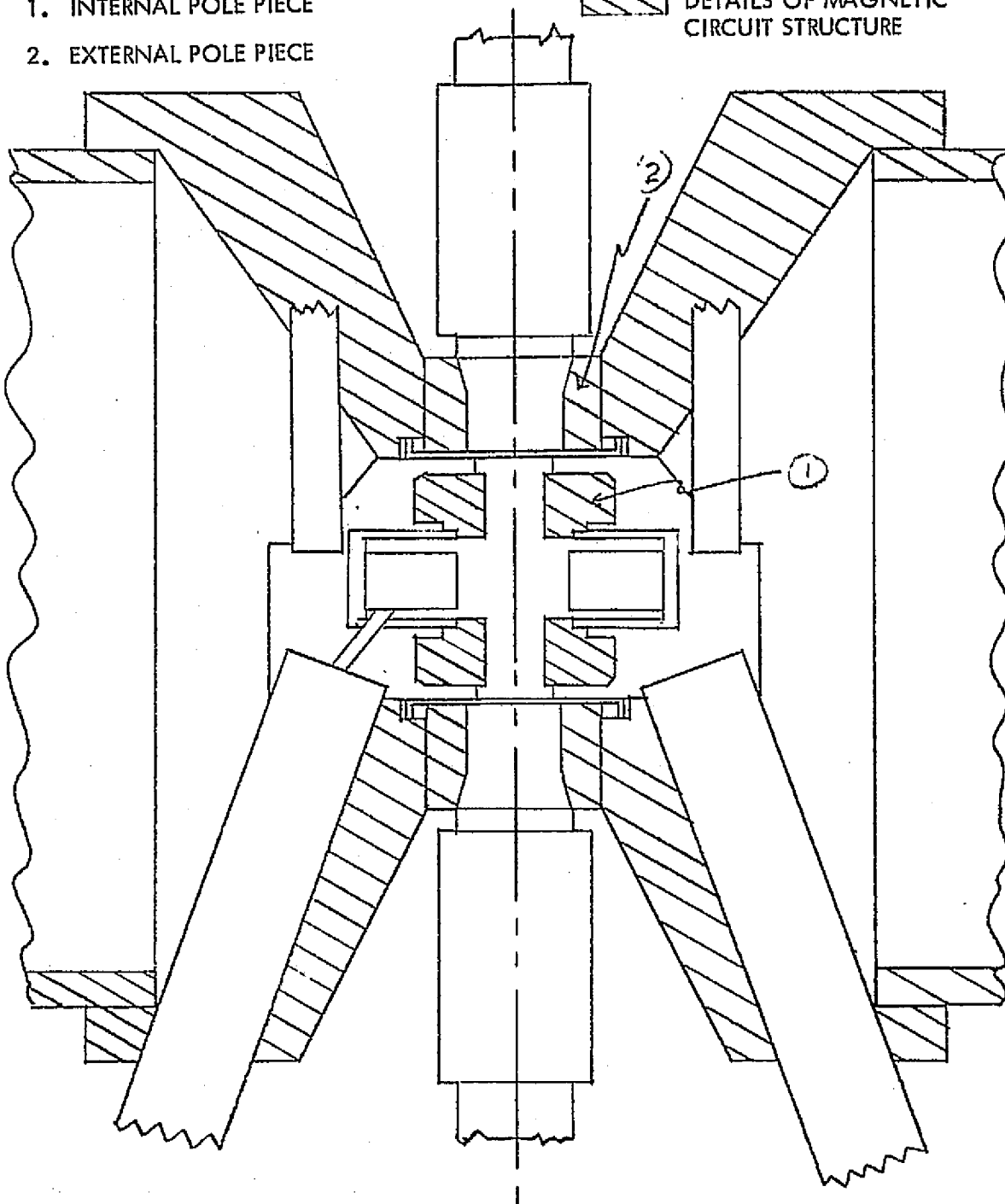


Figure 2-5a. Revised magnetic circuit indicating the portions internal to the tube and the portions external to the tube. Axial symmetry of magnetic field in interaction area is excellent in this design.

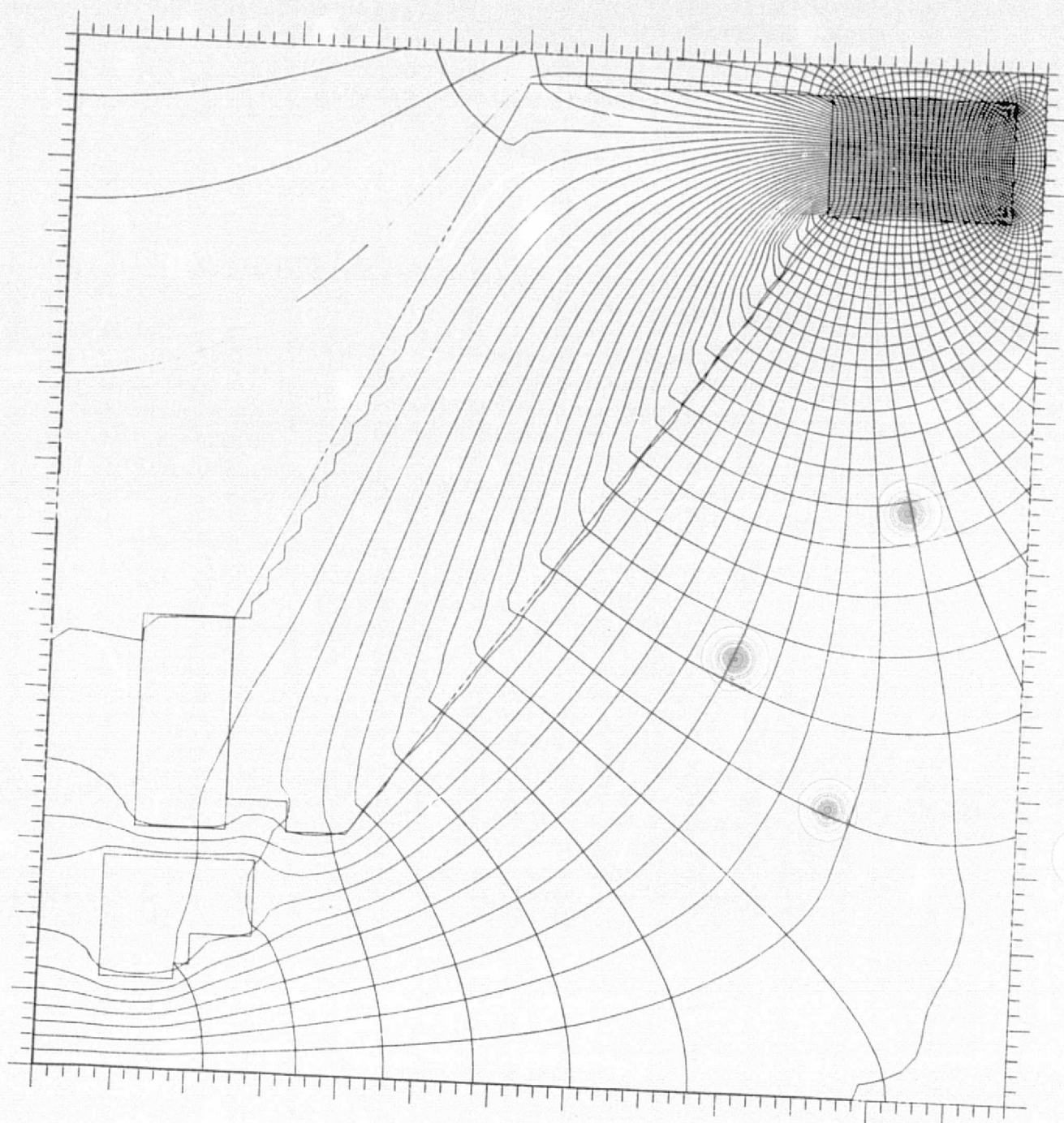


Figure 2-5b. Plot of magnetic flux lines and equipotential surfaces for the magnetic circuit geometry associated with the solenoid type electromagnet used for testing the Amplatron designs QKS1875A and B. Internal pole piece geometry for QKS1875 and C were different. Vertical axis of the tube is at the left hand margin of the plot. The internal upper pole piece is shown in lower left hand corner. The plot was obtained with the use of a special computer program for simulating magnetic flux plots.

The design shown in Figure 2-5 provides a linear relationship between the magnetic flux measured at the center of the gap and the current input to the coil as shown in Figure 2-6. This linearity relationship extends to values of flux density well above those expected to be used, and provides confidence that no distortion is introduced into the magnetic field by saturation effects as the magnetomotive force is increased.

The electromagnet with the QKS1875 Amplitron inserted is shown in Figure 2-15 in Section 2.3.4.

2.2.3 An Adequate Test Facility for Noise and Efficiency Measurements

Noise and efficiency measurements were to be of primary interest and importance for the reasons outlined in Sections 1.2.2, and 2.5.2. How to make these measurements was a critical issue. Noise, in particular, demands an exacting test facility. The noise of greatest importance in the SPS application is random noise outside of a guard band around the carrier. The measuring equipment should be sensitive enough to measure the noise power in any one MHz bandwidth at a level 100 dB below the carrier.

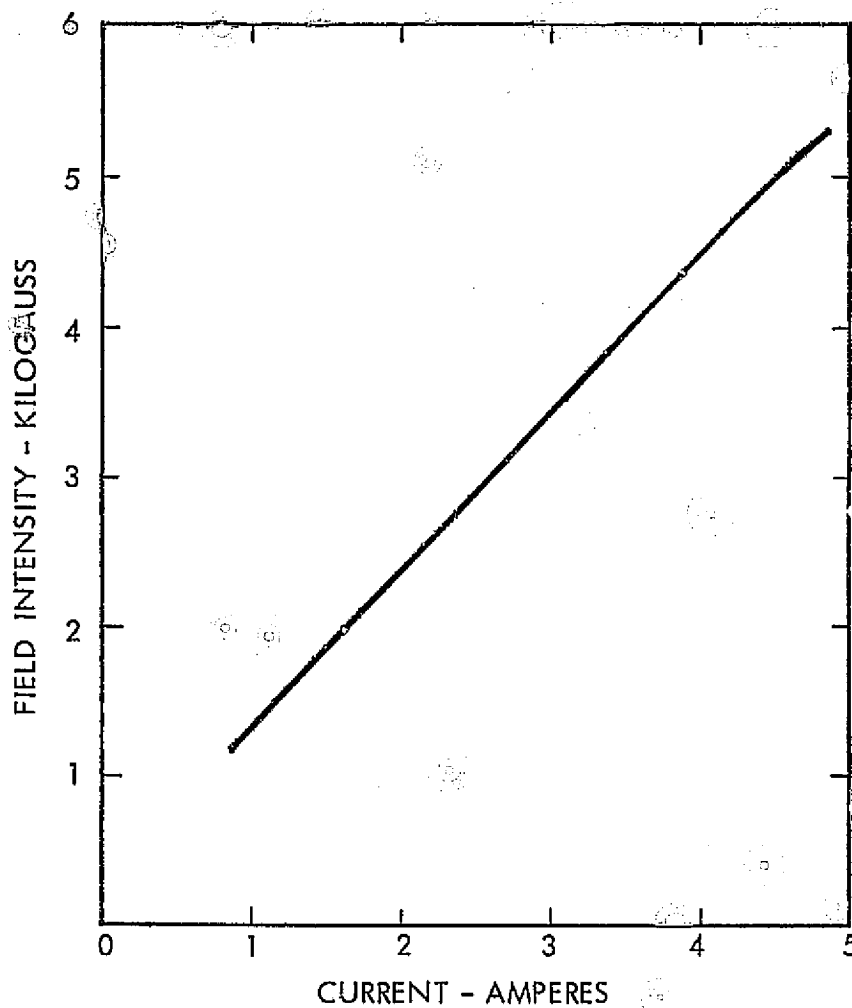
Noise measurements of this sensitivity on an Amplitron are particularly difficult because of the severe requirements placed on the driver. It has to supply a drive level of as much as two kilowatts while having a signal to noise level of 100 dB or more. Usually these requirements would require a large investment in a tube and power supply. Fortunately it had been discovered earlier that an ordinary microwave oven magnetron makes an excellent clean signal source, providing the tube is operated on a well filtered DC power supply and the heater is turned off. Over a period of time considerable data has been taken on microwave oven magnetrons and nearly all such tubes made by several different manufacturers are very quiet when operated in this manner. The magnetron can also be frequency tuned over an adequate amount for this application by varying the reactive component of the microwave load.

The driver set up, provided by Raytheon Company and illustrated in Figure 2-7 was originally test equipment for testing microwave oven magnetrons with a DC power supply over a very broad range of magnetic field, input power level, and load.

The entire test arrangement is shown in Figure 2-8 with a number of the important elements in the set up called out in the caption. Figure 2-9 is a schematic of the test facility. The test facility together with spectrum analyzer and network analyzer has the capability to make the following measurements.

- Phase shift across the Amplitron as a function of various input parameters.
- Measurements of random noise removed from the carrier over a very wide bandwidth.

MAGNETIC FIELD INTENSITY



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Figure 2-6. Plot of on-axis magnetic field as a function of current in solenoid for the geometry shown in Figure 2-5a.

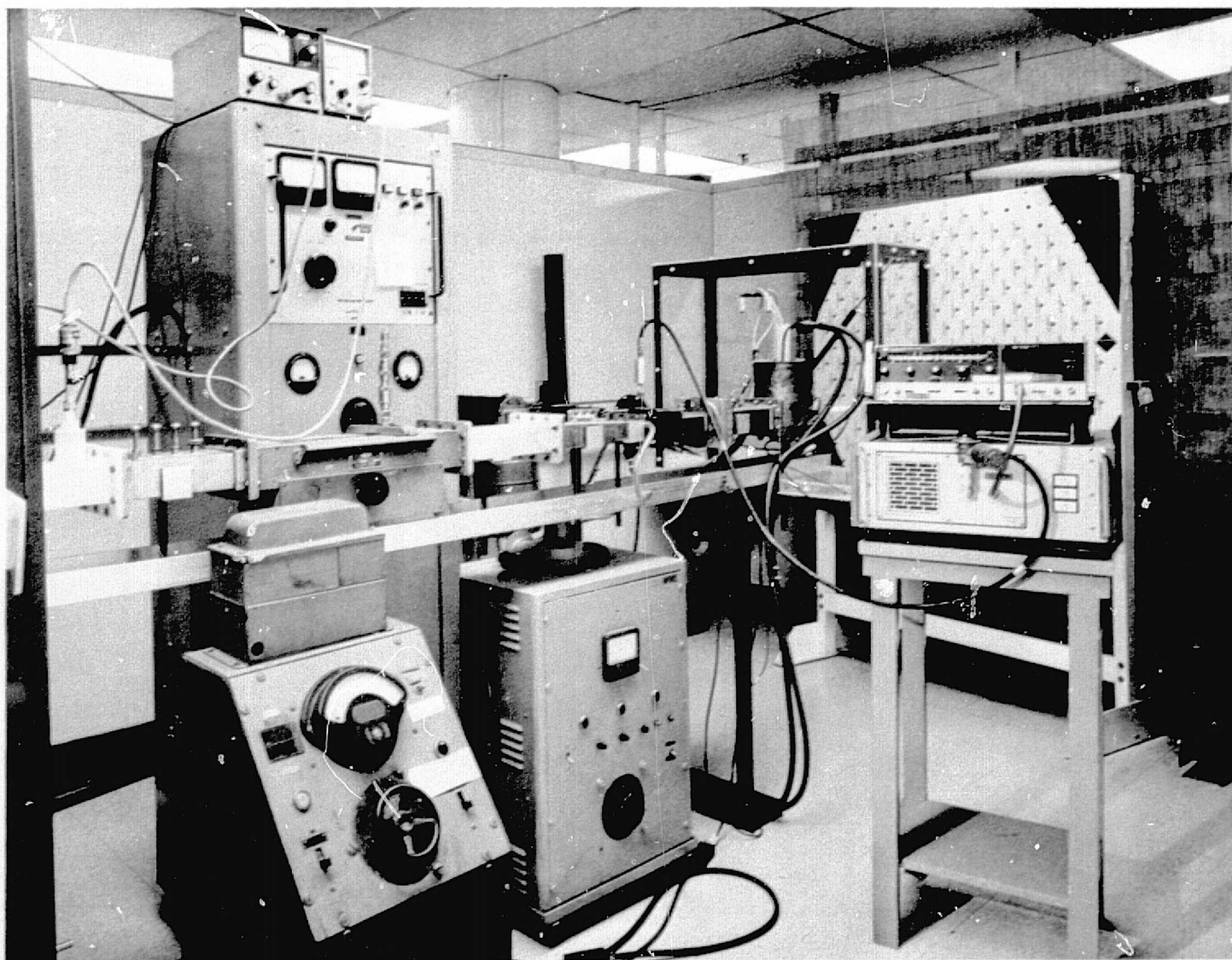


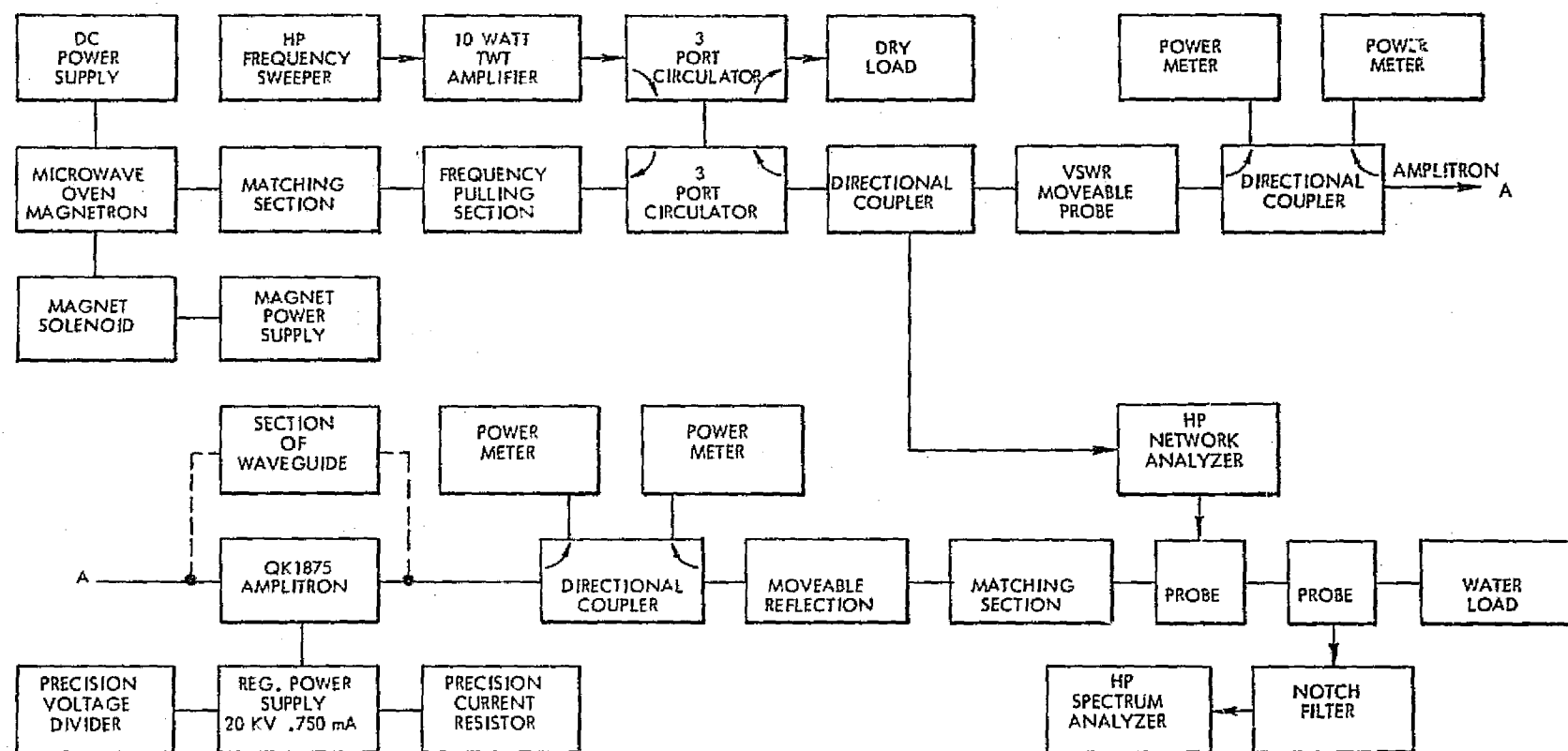
Figure 2-7. Microwave drive source for testing the Amplitron featuring a power level of up to two kilowatts and a very low noise level. The microwave oven tube is operated with no filament power and with a well filtered DC power supply. The tube is supplied with a circumferentially symmetrical magnetic field by means of solenoid magnet. The tube is fitted with a water cooling jacket.

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Figure 2-8.

Assembly of test equipment for development and test of QKS1875 space amplatron. Starting at the right side of the picture: ① frequency swept microwave generator and 10 watt TWT amplifier for locking the frequency of the magnetron ② low-noise magnetron power source with special feature of water cooled anode and solenoid magnetic field to permit operation at the two kilowatt drive level ③ ferrite circulator to permit operation of magnetron as directional amplifier ④ three kilowatt DC power supply for magnetron ⑤ magnet power supplies for magnetron and amplatron ⑥ special solenoid electromagnet for amplatron shown with amplatron in position ⑦ cabinet for housing amplatron under test ⑧ computer for automatically computing efficiency and other parameters from data collected by sensors ⑨ DC 15 kilowatt, 20 kilovolt current and voltage regulated power supply for Amplatron ⑩ HPA spectrum analyzer for out of band noise observations ⑪ HPA microwave network analyzer for cold test and hot test and hot test phase measurements.



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Figure 2-9. Schematic of the Amplitron test facility at Raytheon New Products Center. Equipment corresponds closely to that shown in Figure 2-8.

Sensitivity of noise measurements is greater than 100 dB/MHz below the carrier level with the insertion of a notch filter at the carrier frequency to extend the dynamic range of the spectrum analyzer.

- Measurements of operating voltage level, microwave power output and efficiency as a function of magnetic field, microwave-power drive level, DC input level, and load impedance.

Nearly all of the equipment to make these measurements was supplied by Raytheon Company. Contributions to the test equipment include the low noise magnetron drive unit, magnetrons for that unit, the regulated DC power supply for the Amplitron, the solenoid and power supply for the magnetic field for the Amplitron, miscellaneous power meter, water loads, filters, and ferrite circulators, voltage dividers, and the HPA spectrum analyzer with 8555A, 8552B, 8445B components and HPA network analyzer with 8410B, 8620A, 8418A, 8743 components.

The test facility was also provided with a Tektronix 31 and Tektronix 153 computer and scanner which had the capability of successively scanning a number of sensors and making efficiency or other measurements and recording the results. The system was tested out on the magnetron test unit and was found to work quite satisfactorily. It was not used on checking the amplitrons that were constructed under the work effort, primarily because the testing had not advanced to the stage where sophisticated handling of data was considered essential.

A novel, sensitive, and accurate arrangement for measuring the efficiency and inefficiencies of the Amplitron was investigated. Also investigated was a method to add up all of the losses in the power sinks, including the microwave power output, and comparing it with the DC power coming from the power supply, thus providing a balance sheet method for helping insure the accuracy of measurements and checking on calibration of measuring equipment. Again this arrangement was not used on the Amplitron because the testing had not advanced to the stage where the additional effort involved in activating the proposed system seemed justified.

2.2.4 A Cost Effective Design for Construction, Repair, and for Obtaining a Broad Range of Test Data

A very critical issue at the start of the work effort was the mechanical design of the tube. The electrical design of the slow wave structure had already been decided upon and an anode had been constructed and even some cold test data obtained before the start of the work effort. It was also known that the tube was to have a conventional vacuum envelope around it, that the anode and cathode were to be water cooled, and that it would be highly desirable to have the pole piece structure electrically isolated for DC potential so that

leakage current from the interaction area could be monitored and to some degree controlled for investigative reasons, by applying potential to the pole pieces. However, there had been no decision on what the overall mechanical design would look like.

It was realized that the tube should be designed for easy repair and so that quick changes in design could be made in response to test data. This consideration dictated a building-block type of construction with the blocks held together with a type of bond that was secure, yet which could be easily broken and then remade if occasion demanded.

Also of prime consideration was the cost of the construction of the tubes since the effort had a very modest funding support level. This consideration led in the direction of adapting the design to the use of parts and subassemblies associated with production type electron tubes.

It was further desired that the resulting design could either be used directly or easily modified for various system tests or demonstration of SPS transmitter capability. The design should therefore be reasonably rugged, capable of being packaged with a permanent magnet, and be reasonably economical to construct in limited numbers as well as in larger quantities.

The design that came out of these various considerations is discussed in the next section.

2.3 The Baseline Mechanical Design for the QKS1875; the QKS1875A

2.3.1 Introduction

This section will be devoted to the first design of the QKS1875. Subsequent modifications of the design are discussed in Section 2.6. However, none of the modifications substantially alter the external appearance of the tube or the methods of fabrication. The modifications have been easily accommodated because of the building block like construction of the tube.

It should be restated that many of the broader aspects of the electrical and mechanical design had already been established by the previous design effort on the space tube by George MacMaster and Kenneth Dudley of Raytheon Company. Further, they had made a detailed design of the slow wave structure. This design had been constructed and some cold test data had already been taken prior to this work effort. These were obviously strong inputs into the initial design effort, even though the tapered-vane and center-strapped slow wave circuit design was not used in the final design because of its suspected vulnerability to fabrication problems, an observation that occurred during cold-testing.

2.3.2 The Tube Design

A cross section of the design of the tube is shown in Figure 2-10, while Figure 2-11 shows the appearance of the finished tube. The design of the tube is considered to be a proper response to the following questions:

1. Does the design take the space tube sufficiently into consideration and does it represent a logical step in its development?
2. Does the design permit an adjustment of a large number of input parameters which may impact the efficiency and signal-to-noise ratio?
3. Is the design consistent with the limited amount of effort and funds available for the tube construction phase of the development?
4. Can the tube be easily taken apart, modifications made and then reassembled to reduce the amount of time and expense required when design modifications are indicated to be desirable.
5. Will the resulting tube be in a format to permit its immediate application to terrestrial system use or to limited evaluation in space.

The resulting mechanical design as shown in Figure 2-10 and 2-11 has the features and characteristics which are tabulated below in some detail as an aid in understanding the evolution of the design.

1. The slow wave structure is a mechanically straightforward assembly of constant-thickness vanes and end straps. This construction is an electrically and mechanically proven structure. The constant thickness vanes results in an increase of 35% in the thermal resistance over that of the variable thickness vanes used in the first cold test model of the tube; however, the circuit efficiency is better and thus is a compensating element. In the unlikely occurrence that 10% of the input power is dissipated in anode bombardment and that one vane will have twice the average bombardment, the temperature rise of that vane would be 113°C if the tube is operating at the six kilowatt output level.
2. The internal pole pieces are at cathode potential and serve as end shields. There should be no current flow to them. This zero current flow to the pole faces in the space tube is an essential requirement because of the difficulty of getting rid of any heat which would result from this current flow.

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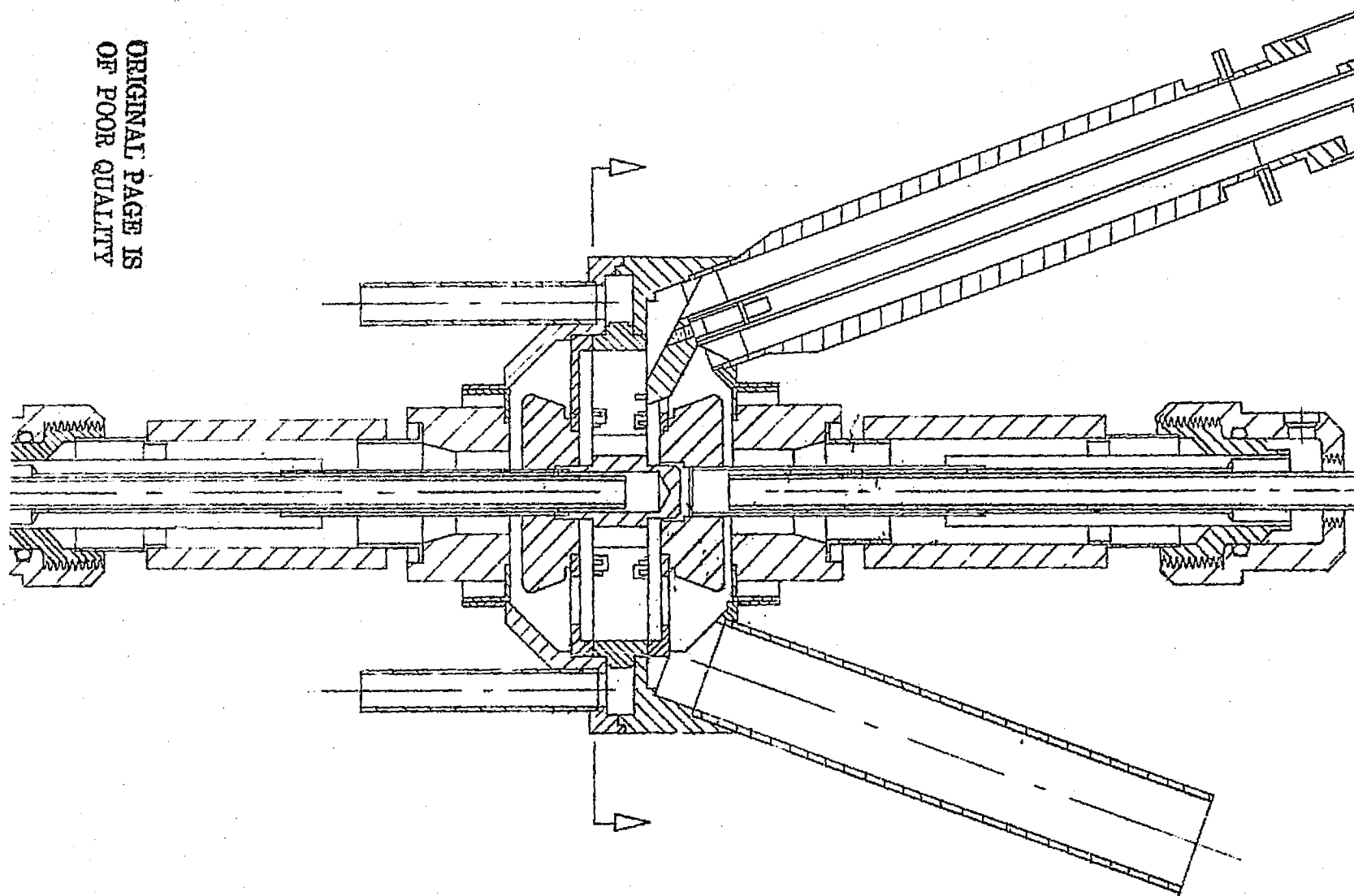


Figure 2-10a. Cross section of the QKS1875 baseline design showing cathode, slow-wave circuit, internal magnetic circuit, connection of the output transmission line and water cooling jacket. Figure is 0.85 of actual size.

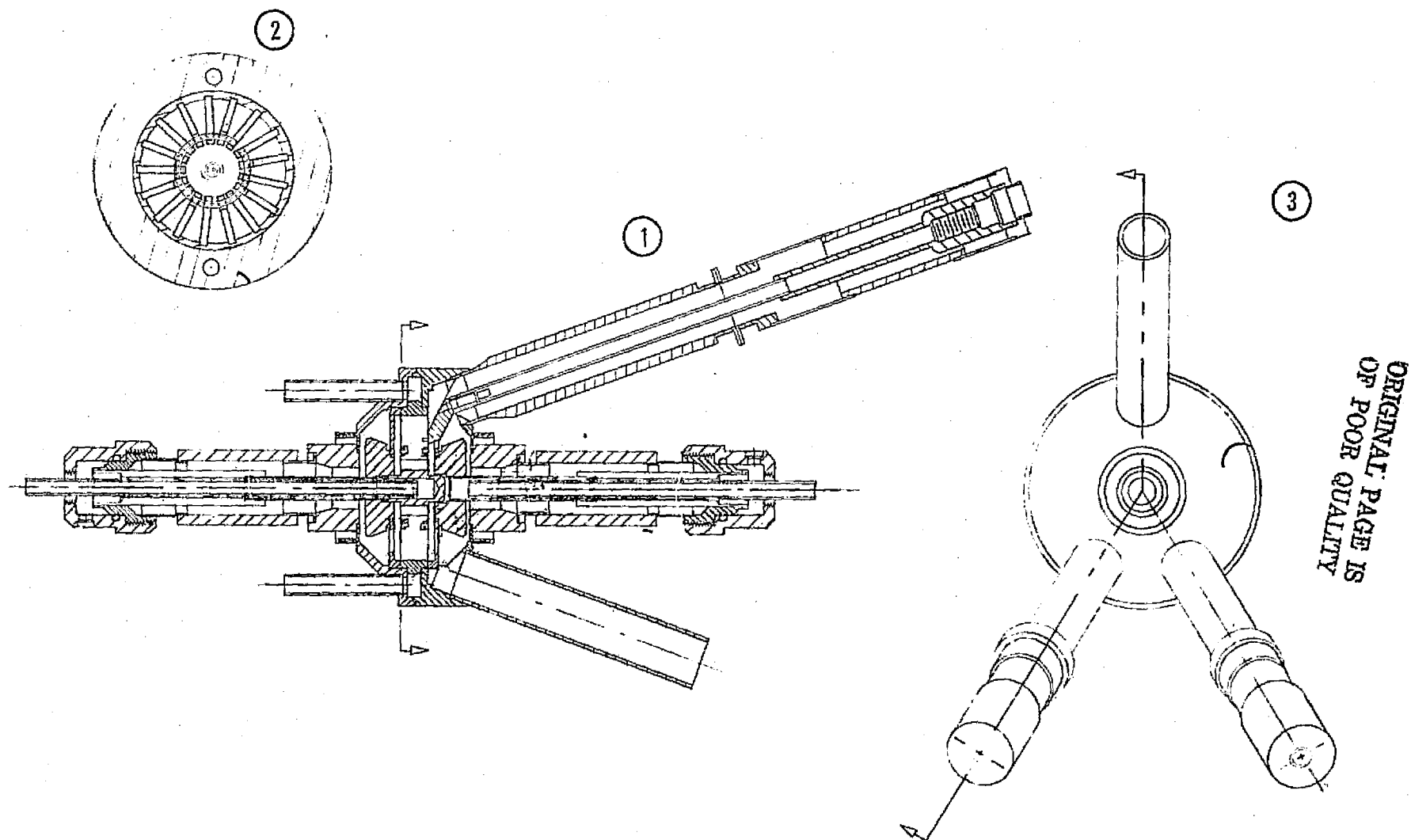


Figure 2-10b. Scaled drawings of QKS1875 showing (1) longitudinal cross section (2) cross section of slow wave network, and (3) external top view.

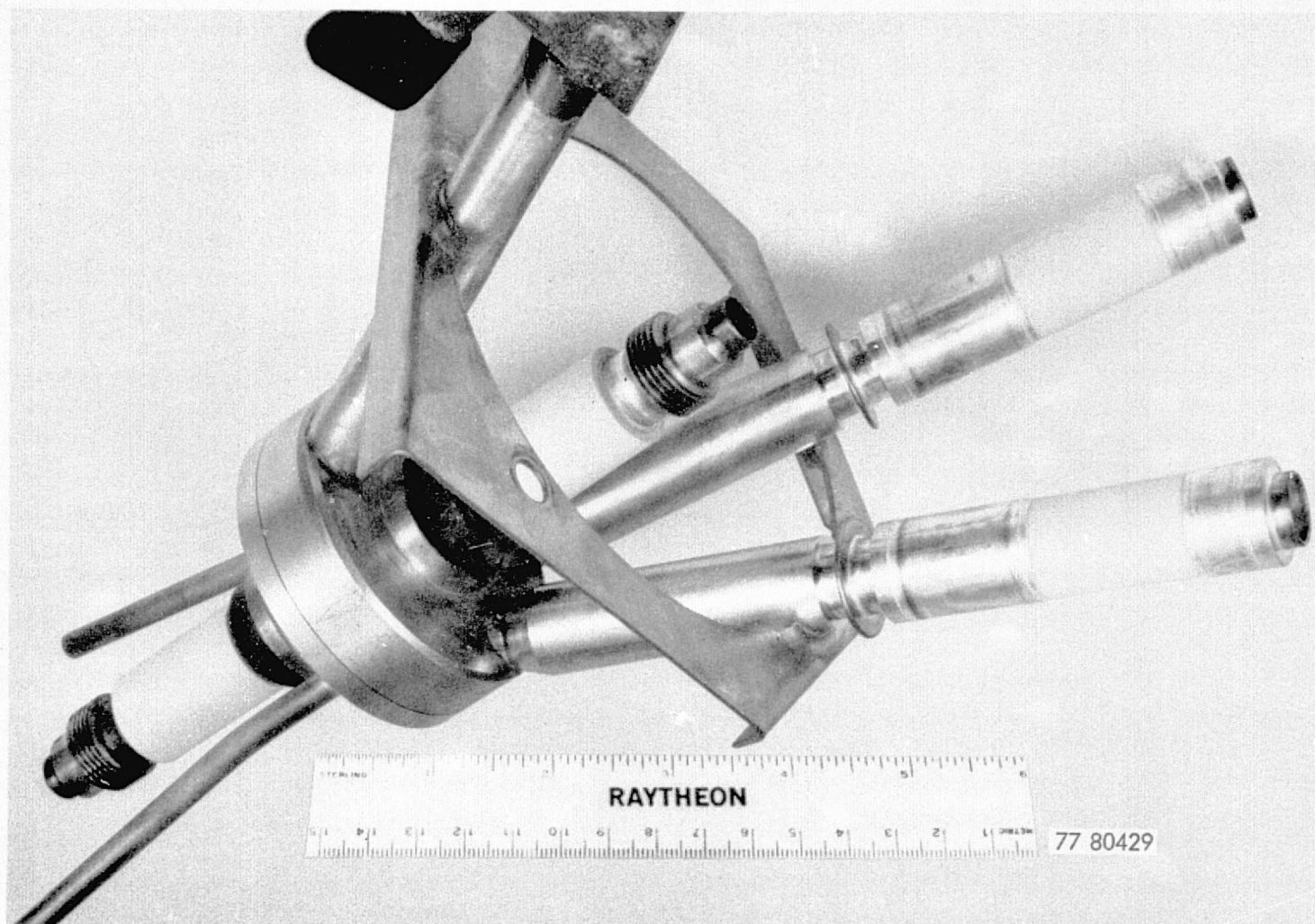


Figure 2-11. QKS1875 Amplatron as sealed off after exhaust. The input and output microwave ports are at the right of the photograph. The cathode terminal and ceramic insulating bushing is at the lower left. The ceramic bushing supporting the internal pole piece is at the center of the picture. The exhaust port is at the top of the picture.

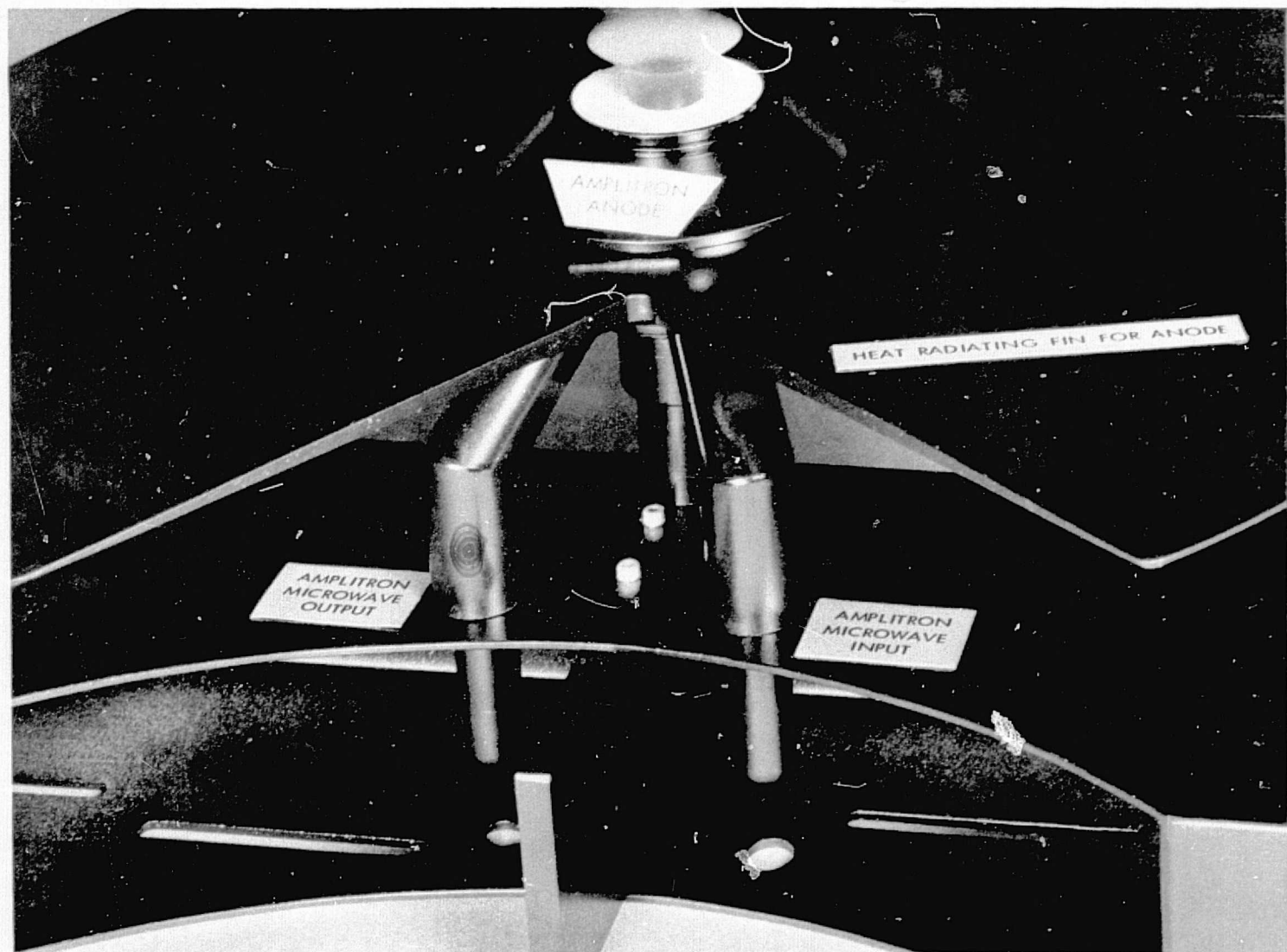
3. Because the pole pieces are at cathode potential there is no need to have a clearance between the inner diameter of the pole piece and the diameter of the cathode support. Thus convex barreling of the magnetic field in the interaction area may be accomplished more easily. Further, there is a much larger cross sectional area of the cathode support for carrying heat away from the cathode in the space tube, or, in the present tube development, for allowing magnetic field modification by insertion of magnetically permeable material inside of the cathode.
4. The design is a double ended structure with isolated tail pole piece which permits (1) the monitoring of electron drift to the pole pieces as a function of potential deviation from that of the cathode, (2) the monitoring of efficiency and noise level as a function of the same potential deviation, and (3) the monitoring of the current flow from any beta emitter which may be placed on the pole face to investigate its role in initiating cathode current flow.
5. A hollow secondary emitting cathode which (1) permits the introduction of cooling water to monitor the amount of back bombardment, and (2) permits some modification of the configuration of the magnetic field while the tube is being tested to examine the impact of magnetic field trimming upon efficiency, noise level, and leakage of current from the interaction area.
6. Rugged but simply constructed input and output pipes needed for handling high CW power levels with low loss; with an option to cool the center conductor if that should be found desirable for any reason. The input and output pipes also represent the coaxial portion of a coax-to-waveguide transition.
7. Geometric and electrical symmetry of the input and output pipes and their connection to the symmetrically slow wave construction to provide an option to reverse the magnetic field and the direction of directional gain in the tube.
8. An assembly which will hold the cathode and the pole pieces precisely centered with respect to the anode bore, thus assuring that the cathode-to-anode spacing will be held precisely and that the magnetic field will be symmetrical. The key to this is the ceramic pole-piece support whose center hole is jigged concentric to the anode bore during the assembly. This center hole then engages a shoulder

on the pole piece which is held concentric to the center hole of the pole piece which engages the outside diameter of the cathode support. It is expected that all of the tolerances which are involved in centering the cathode will add to no more than five thousandths of an inch.

9. An assembly in which the separation between pole faces and the anode is kept to precise tolerances by means of the ceramic pole support. Any tolerances in the axial dimensions of parts and assemblies is cancelled out by positioning the pole piece on the ceramic before heliarc welding the pole piece support into position. The precise axial positioning of the pole faces will provide an axially symmetric magnetic field which will encourage symmetrical behavior of the space charge at opposite ends of the interaction area. The assurance of the proper spacing will also minimize the possibility of arcing between pole piece and the anode.
10. The pole piece centering and positioning ceramic in this tube may well become the only needed support for the pole pieces and the cathode assembly in the space tube.
11. The cathode pole-piece assembly and tail pole-piece assembly may be easily removed from the tube for inspection by breaking the heliarc weld. A repaired, new, or different assembly may then be reinserted and welded without destroying the rest of the tube. One of the more interesting aspects of this procedure is that the details of the magnetic field may be changed by replacing the internal pole pieces of the tube.

2.3.3 Comparison of the Tube Design With the Ultimate Space Tube With Respect to the Arrangement of Input and Output Pipes

Figure 2-12 in context with Figure 2-11 will help to clarify the differences between the output and input terminations of the space tube and the tube that was constructed. The model whose photograph is identified as Figure 2-12 was constructed with Raytheon exhibition funds for an AIAA Conference in Washington D.C. and shows how the space tube looks and interfaces with a section of the radiating antenna. A section of the heat radiating fin is cut away to expose the interface between the input and output and the radiating slotted waveguide. The model of Figure 2-12 shows the input and output connected to a slotted waveguide for direct radiation into space. This is one of the interface options between the tube and the transmitting antenna. However, the geometry of the interface with the waveguide would be the same as that required in Figure 1-4 in which there is an intermediate section of feed waveguide between the tube and the slotted waveguide array.



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Figure 2-12. Mechanical mockup showing integration of proposed space Amplitron into the slotted waveguide radiator. The same general arrangement applies to the packaging concept of Figure 1-4 but the waveguide shown in the above figure becomes the feed waveguide for the slotted waveguide array of Figure 1-4.

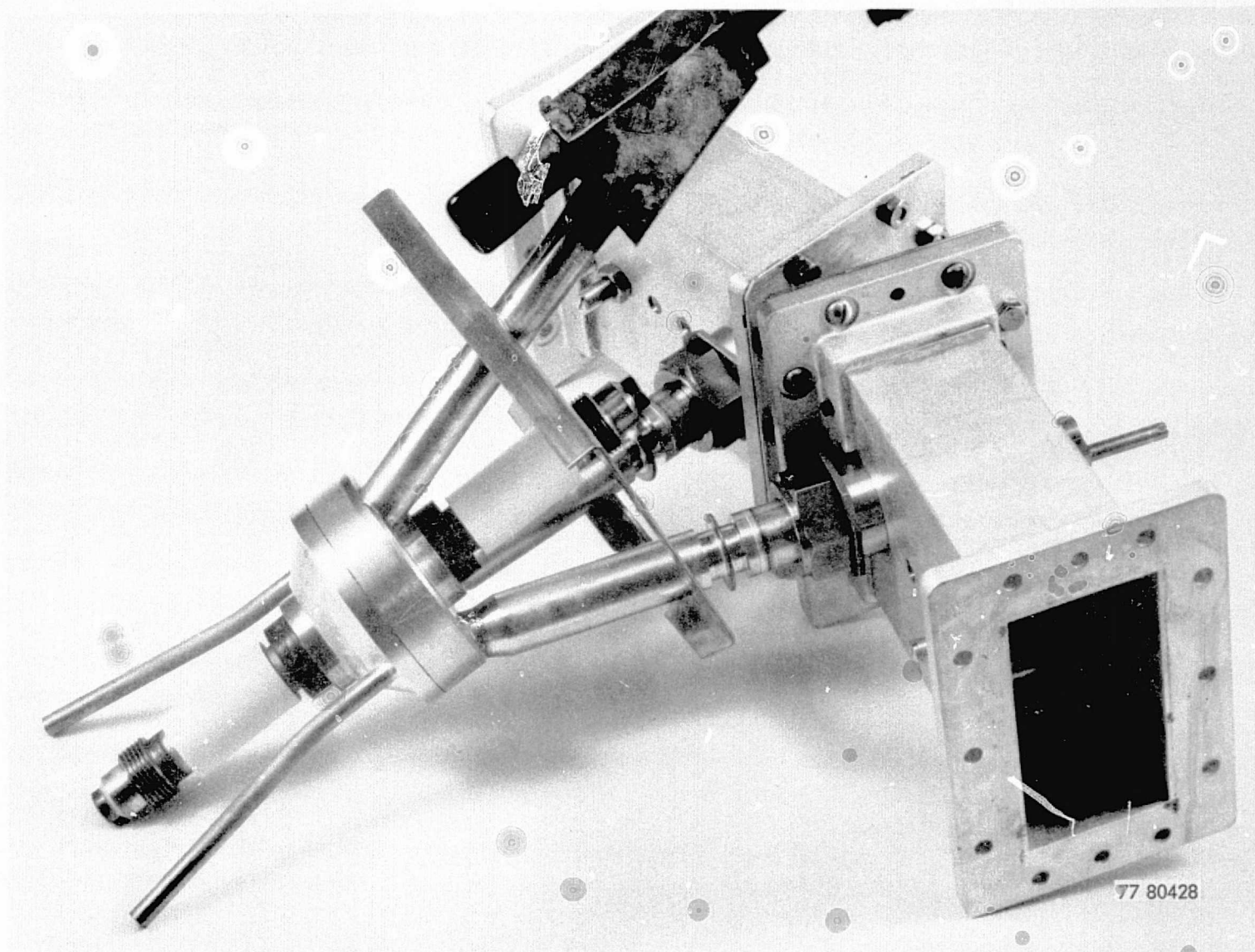
The space tube requires that the plane of the anode be parallel to the plane of the waveguide in order that a cooling radiator may be attached to the tube and efficiently radiate. In order that the input pipe not interfere with the attachment of this radiator they are brought out of the structure at an angle; they are not brought straight down because of a probable interference with the permanent magnet design and the arrangements that will have to be made in a subsequent development phase to vary the magnetic field intensity. In order to meet the requirement of parallelism between the anode radiator plane and the waveguide plane a bend has to be made in the output and input pipe in the space tube. However, this bend is not required in the first phase of the tube development and its incorporation would represent a considerable increase in the mechanical complexity and cost of the tube.

2.3.4 Pictorial Description of the Assembly of the Tube to the Input and Output Waveguide Transitions

Figures 2-13, 2-14, and 2-15 show how the finished QKS1875 is fitted into the coax to waveguide transitions. The type of transition used is a doorknob transition. A more conventional transition would have been the probe type in which the tip of the antenna would have been enclosed in a ceramic dome. However, this construction would have cancelled the option of being able to cool the center conductor.

The methods of joining the QKS1875 outputs to the waveguide transition are critical enough to merit some discussion. In the initial procedure the tip of the output was firmly seated in the doorknob by means of a clamping arrangement while the inboard side of the output was firmly attached to the other side of the waveguide by a tapered sleeve clamping arrangement. Thus both sides were firmly secured so that if there was differential expansion between the QKS1875 output and the waveguide the ceramic and the ceramic-to-metal seal would be put under tension or compression. This arrangement was later modified by fitting the outboard end of the output to the doorknob by means of a spring sleeve which eliminated the differential expansion problem if there were to be one. Thus a photograph taken of the current procedure would be slightly different from that of Figure 2-14 which was taken of the earlier procedure. The new photograph would show a spring sleeve extending up to and slightly over the edge of the outboard ceramic to metal seal. Another purpose of the sleeve was to enclose the feather edge ceramic to metal seal and remove its vulnerability to the concentration of high electric field lines.

Figure 2-15 shows the assembly of the tube, complete with output transitions, into the solenoid electromagnet. In this arrangement the input and output of the tube can be reversed by rotating the tube within the solenoid and then tipping the solenoid in the opposite direction to maintain the horizontal orientation of the waveguide in the test set up.



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Figure 2-13. QKS1875 Amplitron with waveguide transitions attached. The coax to waveguide transitions are of the "doorknob" type.

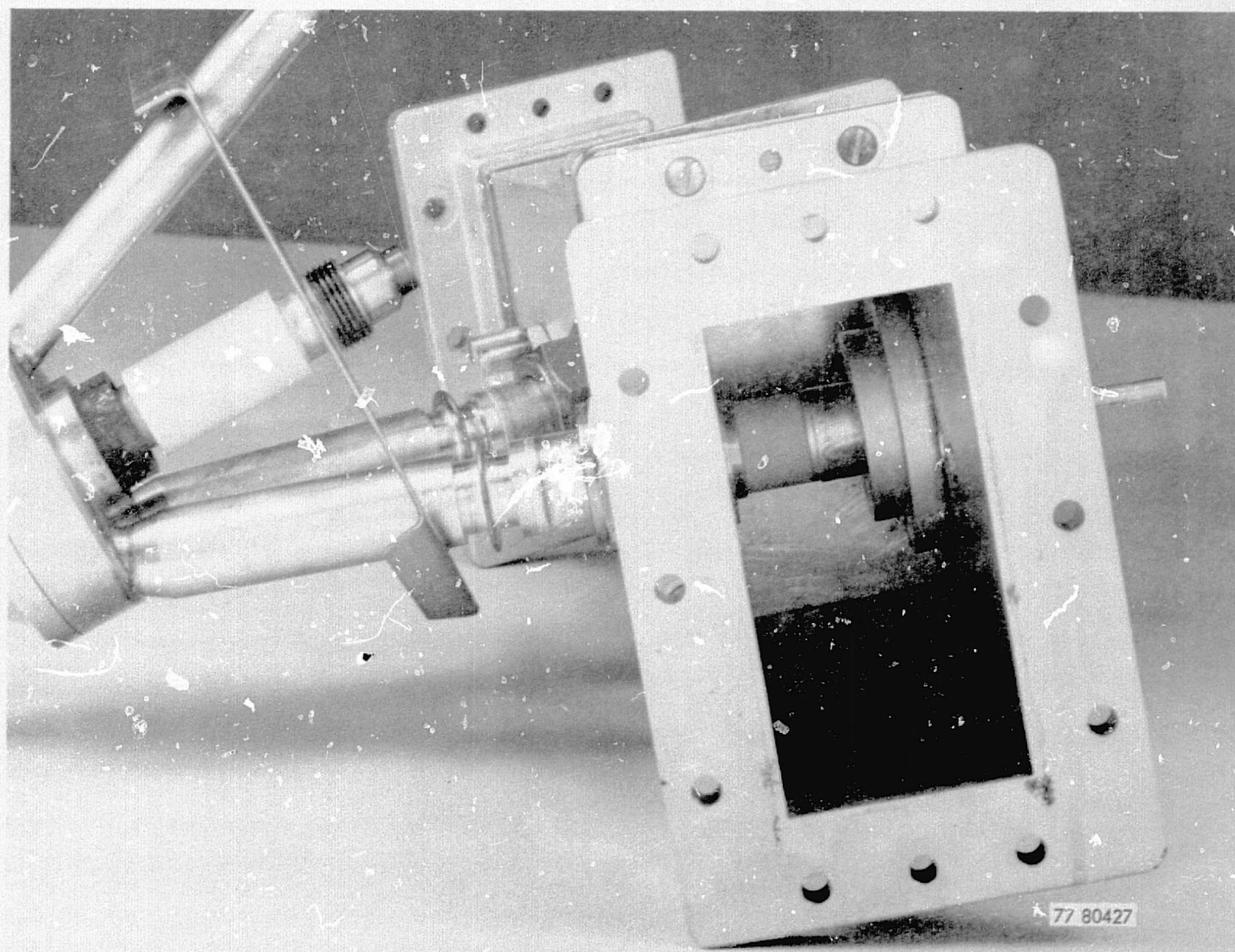


Figure 2-14. Closup view of coax to waveguide transition of QKS1875 Amplitron showing the "door-knob" type transition. The small tube protruding at the right of the picture is a connection to the center conductor of the coax line which permits optional insertion of liquid cooling and instrumentation to within one inch of the connection of the center conductor to the slow wave network.

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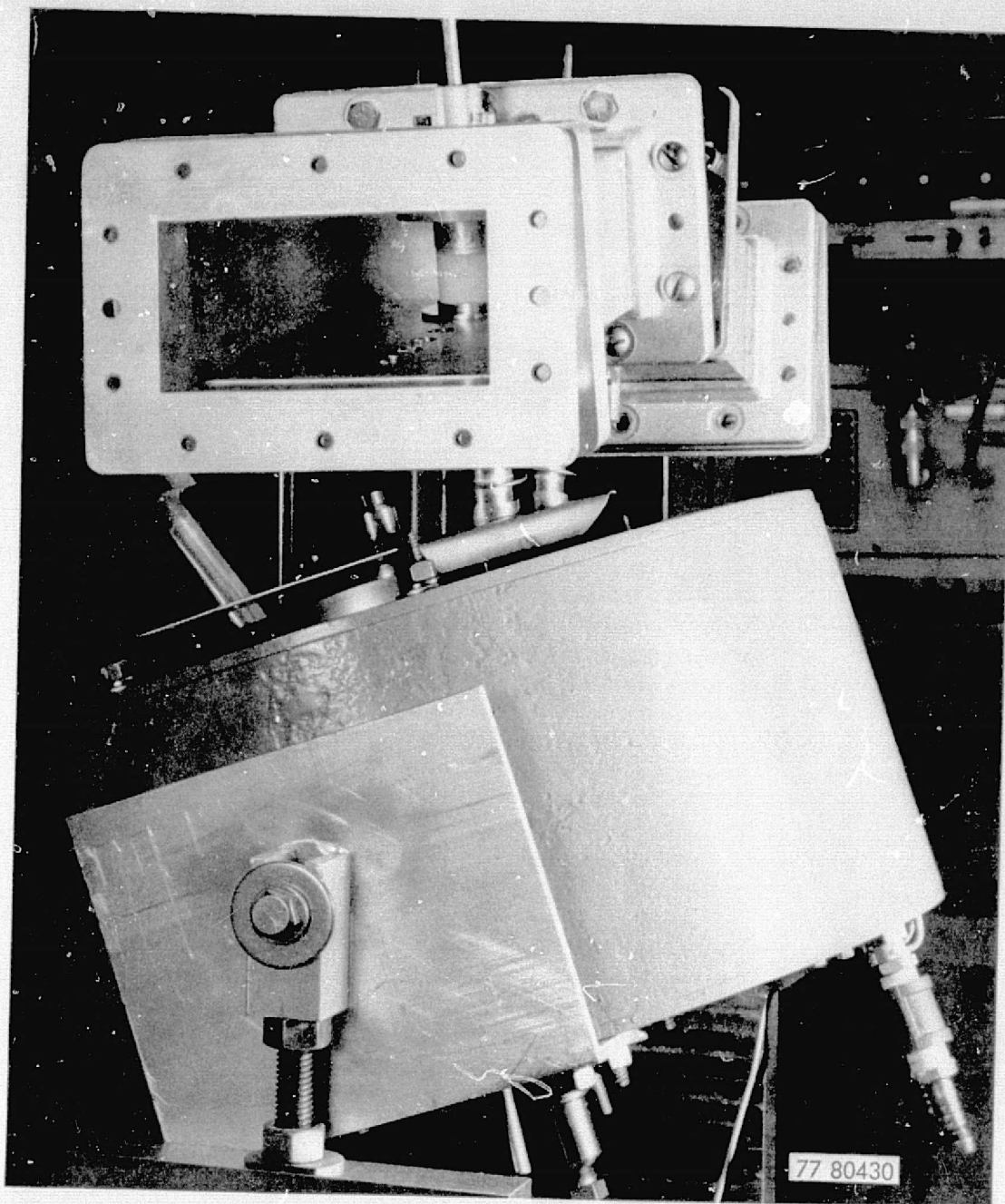


Figure 2-15. QKS1875 inserted into solenoid magnet ready for positioning in test set up. Water cooling connection to cathode and its associated pole face is seen protruding from bottom of center of solenoid. Other pole face may also be liquid or air cooled if desired. The solenoid magnet and tube assembly may be rotated around magnet support and raised or lowered for precision fitting to the test system.

2.3.5

Pictorial and Narrative Description of the Tube Assembly

The following material is intended to take the reader through the general assembly procedure with a combination of pictorial and narrative material.

- Anode Assembly

Figure 2-16 shows the anode or slow-wave circuit assembly. The anode assembly consists of an outside anode cylinder, vanes, and straps. The vanes are machined from copper with the slots for the straps machined with a radius to accommodate the curvature of the straps. The back wall is slotted to accurately locate the vanes. A stainless steel pin which is slotted accurately positions the tips of vanes facing the cathode. The whole assembly is brazed together with silver solder in a suitable atmosphere.

- End Dome (Sometimes Called Cover) and Ceramic Support Assembly

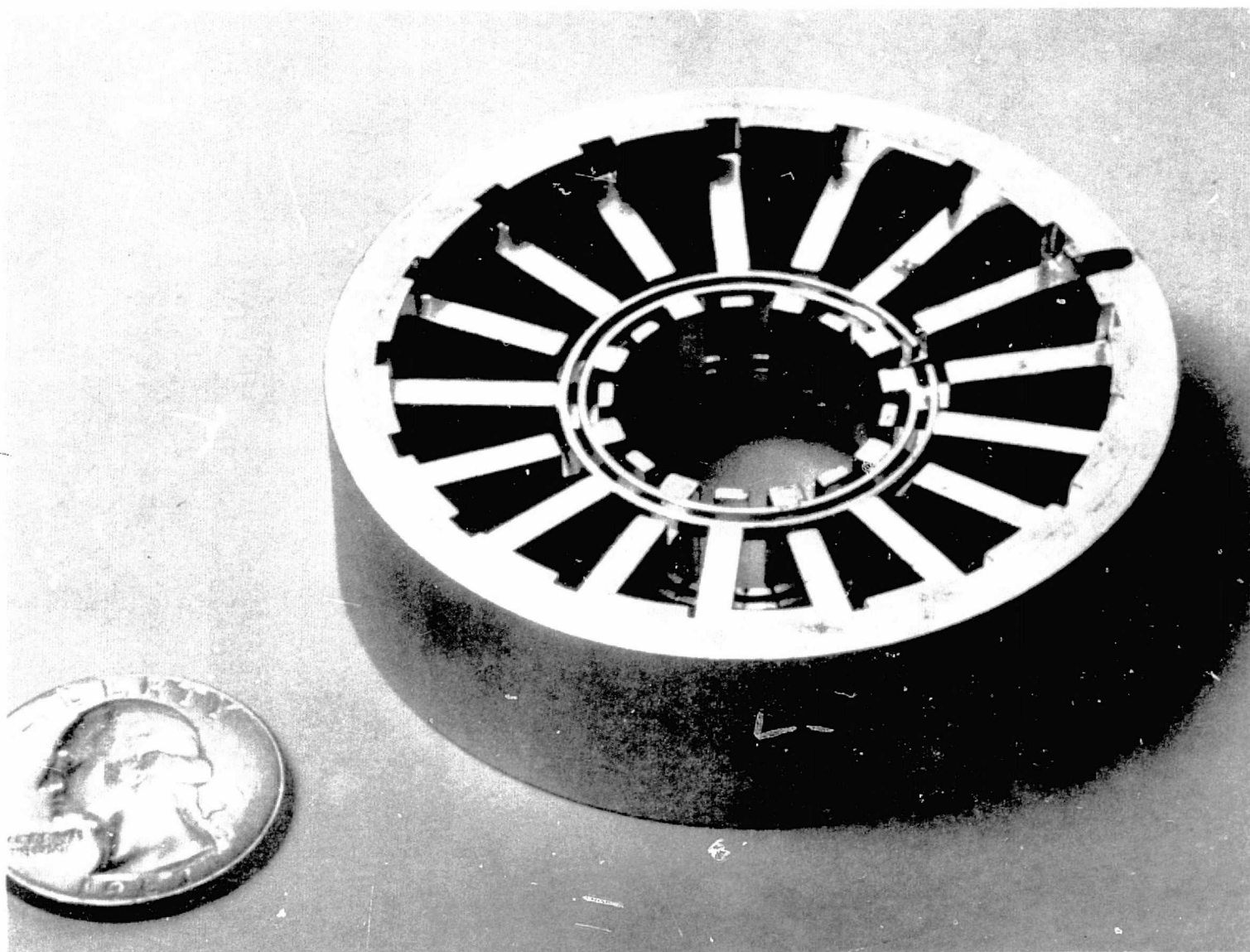
Figure 2-17 shows how the two support insulators are fitted into the two end domes and center the pole piece and also axially position it. The outer and inner diameters of the ceramic support and their concentricity are held to sufficiently tight tolerances to locate the pole-piece and cathode accurately on center. The pole piece is not assembled at this time but is shown in Figure 2-17 for explanation purposes. There are no brazing operations involved in this assembly. The figure also shows the platinum clad cathode brazed to the pole piece.

- Anode - End Dome Assembly

Figure 2-18 shows how the anode is positioned within the cover over the ceramic support. There is no braze at this time, but the figure shows how the deep groove in the end dome and the anode form the bottom and inside of the water jacket when the assembly is brazed later.

- Brazed Anode and End-Dome Assembly

Figure 2-19 shows the first brazed assembly. The top ceramic support and end-dome that supports the two output pipes are added to the previously discussed assembly and then the whole assembly is brazed together. The cathode is not a part of that assembly but is shown for orientation purposes.



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Figure 2-16.

First Brazed slow-wave structure assembly utilizing constant thickness vanes and end strapping.

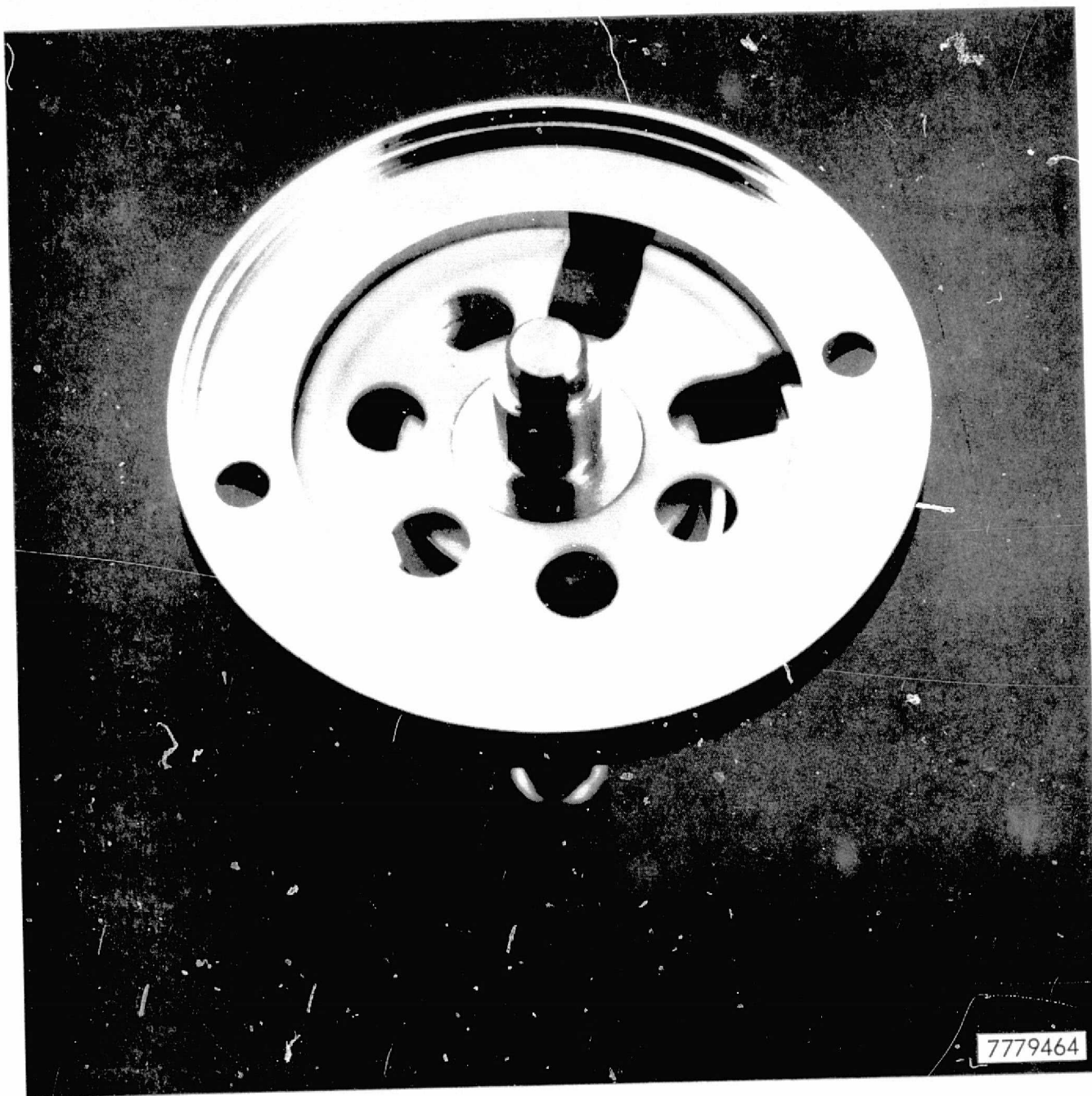
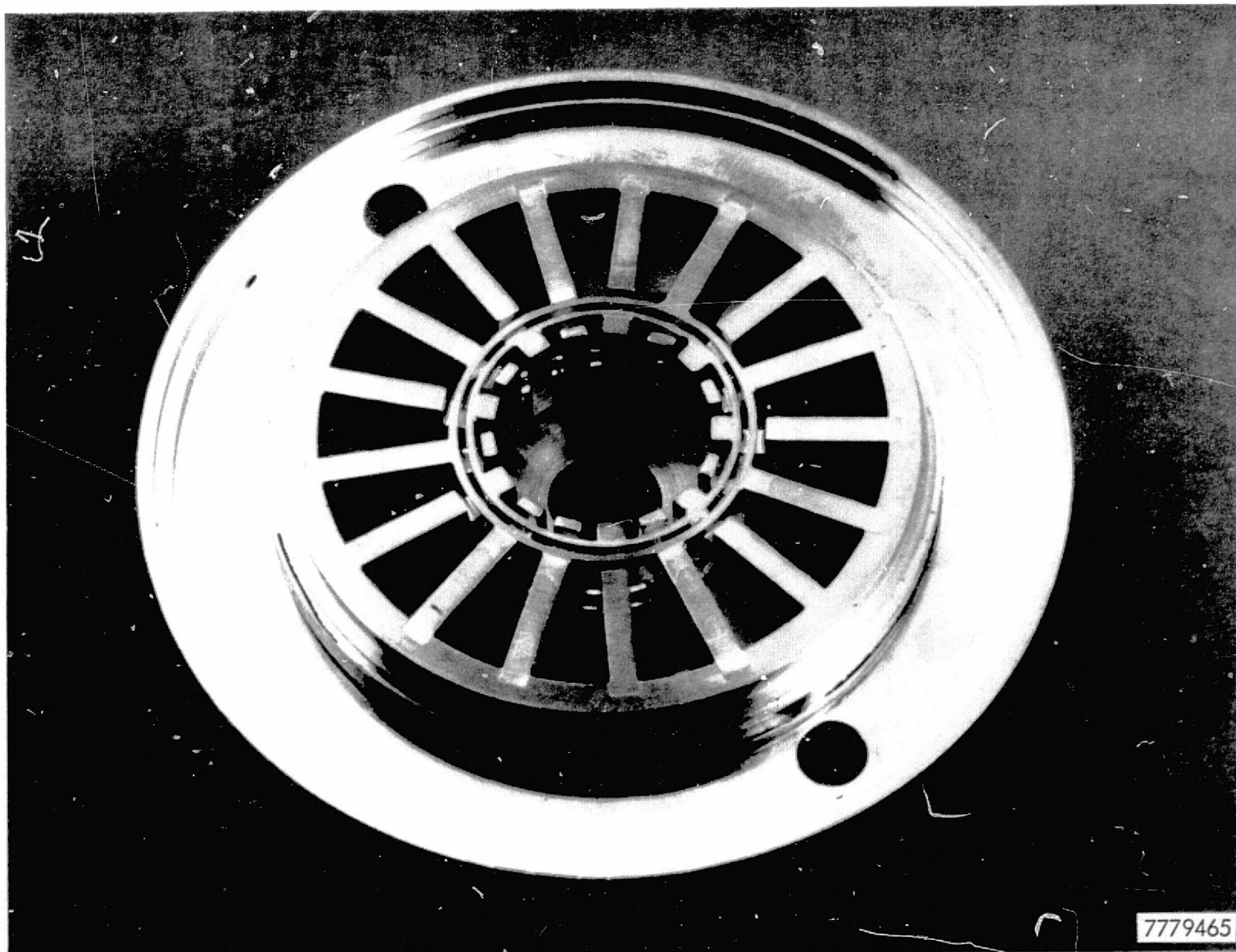


Figure 2-17. Assembly showing cathode end dome, ceramic spider, cathode support pole piece, and water cooled, platinum-clad, secondary emitting cathode.



77 Figure 2-18. Anode-End Dome Assembly. Anode is positioned over the ceramic spider support and within the end dome.

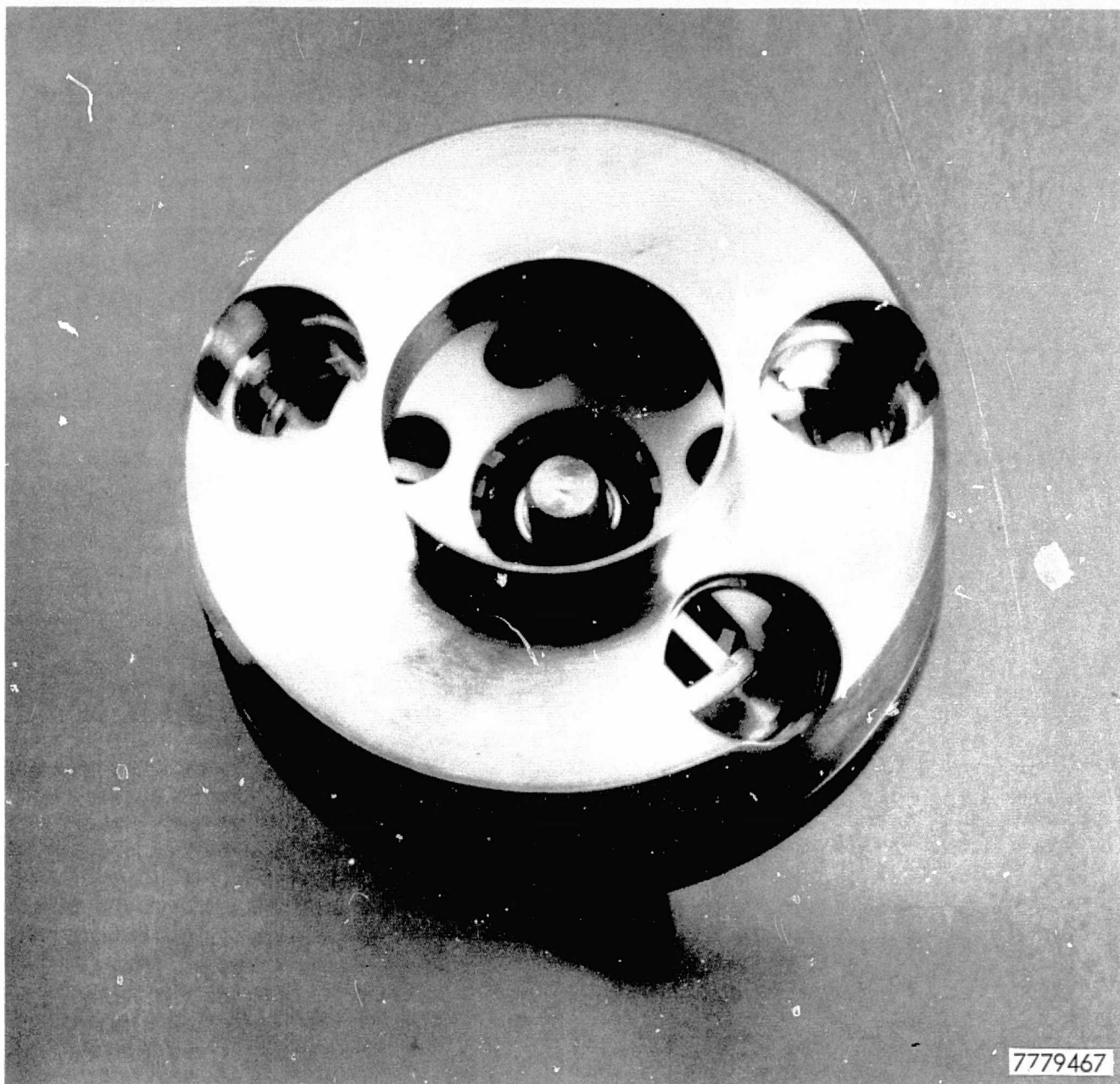


Figure 2-19. Brazed Anode and End-Dome Assembly. This is the first brazed assembly. The cathode is not a part of that assembly but is shown for orientation purposes.

- Assembly of Input and Output Pipe to the Anode and End Dome Assembly

Figure 2-20 shows how the input and output are assembled to the tube. The outer conductor of the coax line is assembled to the outer conductor portion of the impedance matching transformer that is shown in more detail in Figure 2-1. This assembly is then inserted into the tube and the two feet of the assembly secured to the tops of the vanes with socket head cap screws. (The electrical bond is a brazed bond when the assembly is brazed) Then the center conductor assembly is inserted into the output pipe and its connection made to an anode vane by means of a tongue and slot joint which is brazed together when the whole assembly is brazed.

The exhaust pipe is then inserted, and the whole assembly is then put through the brazing oven in a jig which also supports a thin plate. The thin plate is brazed to the two outputs and the exhaust pipe to provide mechanical strength and support for the two output pipes.

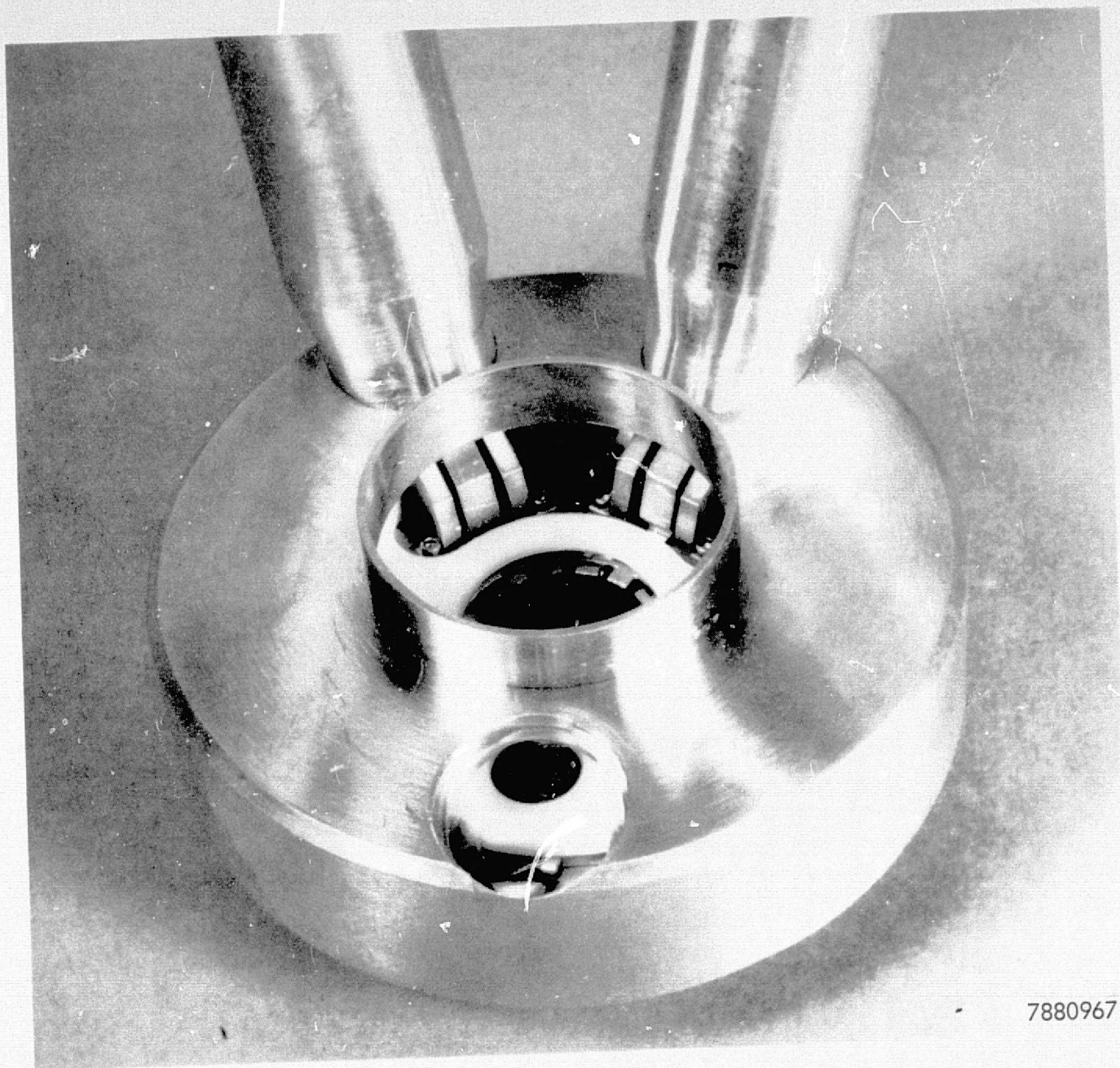
The whole assembly as it comes out of the brazing oven will then look like Figure 2-11 except for the cathode and tail pole piece assemblies which are assembled to the tube at a later stage. The center conductor of the coaxial output has been left free to move inside of the outer conductor during the brazing in order to accommodate a rather large differential expansion between the inner and outer conductor assemblies.

- Final Assembly of Tube

The final assembly of the tube consists of four heliarc welds. The cathode pole piece assembly is dropped into the tube and its centering is self jugged by means of the support ceramic shown in Figure 2-17. Then a heliarc weld is made. Then the tail-pole piece assembly is dropped into place and similarly positioned. It is then bonded to the rest of the tube by means of a heliarc weld. Finally a heliarc weld is made between protruding lips on the center and outer conductor at the extreme outboard end of the output and input pipes. See Figure 2-11.

The tube is then ready for exhaust.

2.4 Application of Crossed-Field Tube Electron Dynamics and Circuit Theory to the Design of the QKS1875 Amplitron



7880967

Figure 2-20. Assembly of input and output pipe to the anode and End Dome Assembly.

2.4.1 Introduction

This section consists of essentially three parts as follows:

- (1) Theory, design, and impedance and phase shift properties of the slow wave circuit.
- (2) Design of interaction area of tube to provide voltage, current, magnetic field relationships as function of number of space charge spokes.
- (3) Superposition of slow wave structure parameters and interaction area to define operating characteristics. $\omega\beta$ diagram.

The impedance matching of the slow wave network to the input and output transmission lines is treated as a separate subject in Section 2.2.1 because of its novel form which has been necessitated by cooling considerations for the space tube.

2.4.2 Theory, Design, and Impedance and Phase Shift Properties of the Slow Wave Circuit.

The slow wave circuit which has been used for the QKS1875 Amplitron design is a vane and strap design configuration. The circuit equivalent which has been found to well represent the network behavior in the frequency region of interest is sixteen two terminal pair networks which are connected in cascade. There is a sever between the input and output of the network with very low coupling from input to output across this sever.

Each two terminal pair network appears as shown in Figures 2-21 a and b, in which b defines the nature of the generalized impedances in Figure a. In Figure 2-21b L_s is the strap inductance, C_s is the strap capacity, and Z_c is the input impedance of the cavity formed by the two vanes brazed to the backwall as seen from the point where the straps are brazed to the vanes.

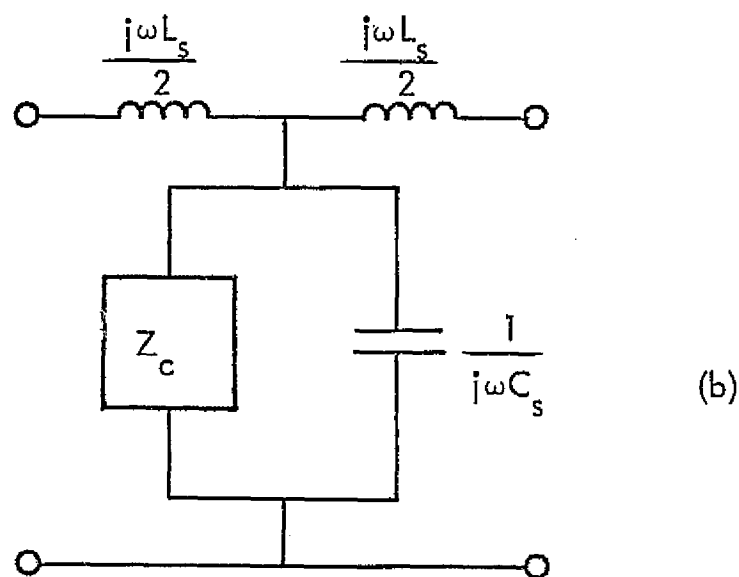
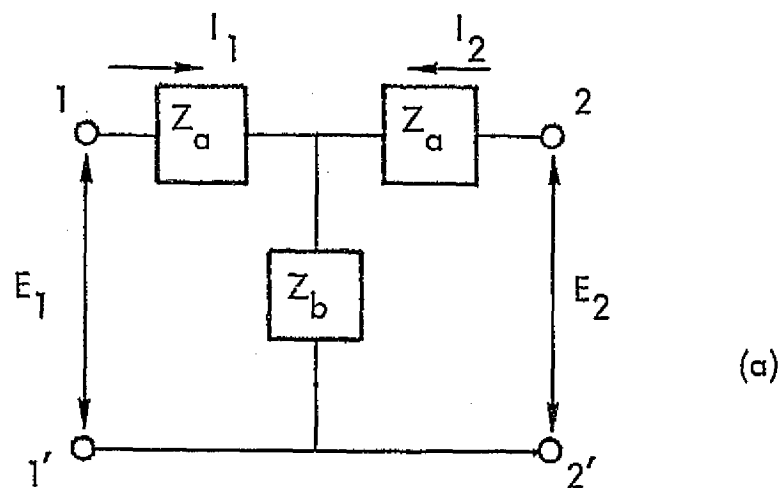
The two terminal-pair network defined by Figure 2-21b has the properties of a low pass filter. The theoretical phase shift is given by the following expression:

$$\theta = \cos^{-1} \frac{Z_{11}}{Z_{12}}$$
$$= \cos^{-1} \left[1 + \frac{L_s}{2L} \left(1 - \frac{\omega^2}{\omega_c^2} \right) \right] \quad (4)$$

in which the impedance Z_c of Figure 2-21b has been replaced by a parallel inductance L and a capacitance C , a reasonable approximation in the phase

C-2

EQUIVALENT CIRCUIT OF NETWORK



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Figure 2-21. Schematic of the impedance representation of the two-terminal pair network which describes the propagating element in the slow wave circuit of the QKS1875.

shift region of interest.

The phase shift properties of the slow wave circuit used in the D design version of the QKS1875, and of the slow wave circuit used in the A, B, and C design version of the QKS1875 were experimentally measured. The results for QKS1875 D are shown in Figure 2-22. The points of data were obtained by coupling lightly to the anode circuit of 16 network sections, first with both ends open, and then with one end shorted to pick up the even and odd integer multiples of 90° phase shift over the length of 16 identical sections and then noting the frequencies of the resonances.

From the experimental measurements of the lower cutoff frequency, ω_c , and the phase shift at one other value of ω , the ratio of $L_s/2L$ of 0.0906 may be found to put into equation 2-4 to provide the "theoretical" phase shift curve shown on Figure 2-22. It is noted that the experimental data and the theoretical curve track each other well over the region of interest.

The selection of the dimensions of the vanes and the straps to obtain the values of Z_s , L_s , and C_s for the proper phase shift at 2450 GHz is partly science and partly art. We were able to achieve the desired phase shift at 2450 MHz within acceptable limits with the first dimensional design of both the 0.400 in. and 0.700 in. long anodes used in the A, B, C, and D designs of the QKS1875, respectively. For design purposes we computed Z_s in Figure 2-21b by using Figure 2-11 and equation 29 in Section 2.5 of Collins "Microwave Magnetrons". (Reference 31)

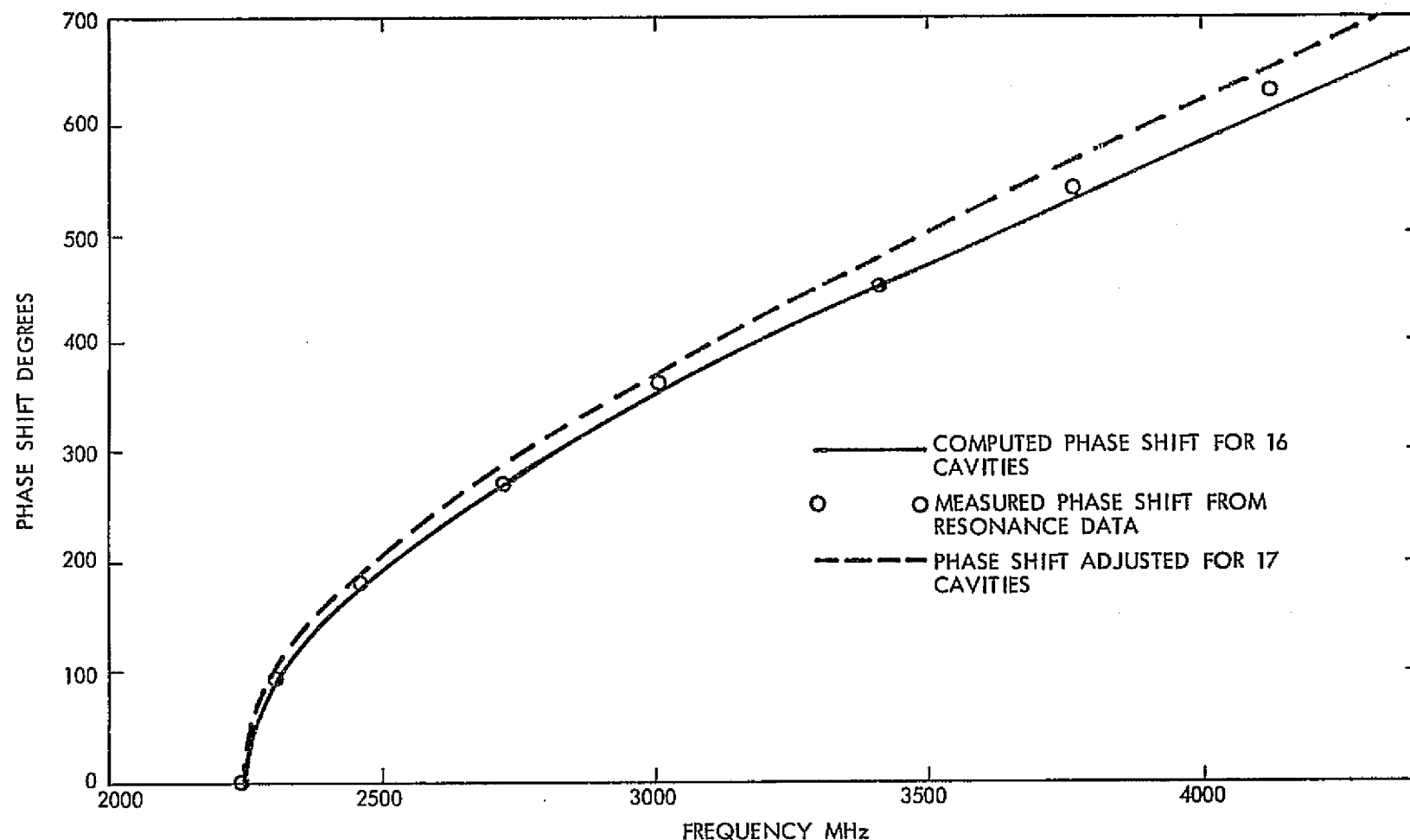
For purposes of comparison the phase shift characteristics of the short 0.400 in. long anode is shown with that of the 0.700 in. long anode in Figure 2-23. The derived value of $\frac{L_s}{2L}$ for the 0.400 in. long anode is 0.062.

The characteristic impedance of this network is also of interest and this can be computed from theory if the ratio $L_s/2L$ and L_s are known. The expression for the mid-series characteristic impedance is:

$$Z_o = \frac{\omega L_s}{2} \sqrt{\frac{4L}{L_s \left(\frac{\omega^2}{\omega_c^2} - 1 \right)}} - 1 \quad (5)$$

If a value of 0.467×10^{-9} Henries is used for $\frac{L_s}{2}$ then at 2450 MHz the characteristic impedance is 73 ohms for the slow wave network used in the A, B, and C, design versions and 77 ohms for the slow wave network used in the D design version slow wave structures.

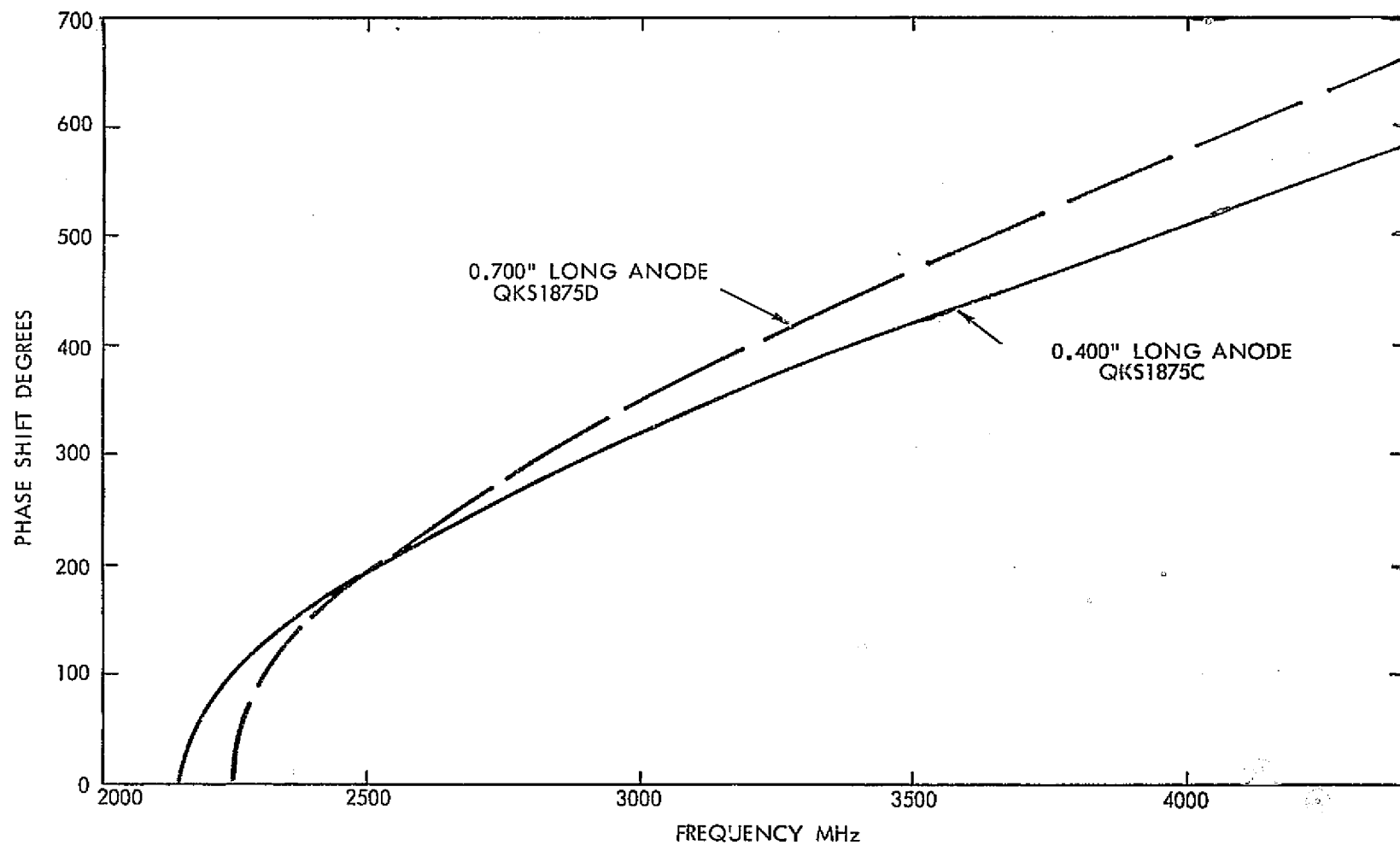
We have discussed briefly the design of the two anodes that were assembled into tubes. Prior to starting this work effort, the Raytheon Company had assembled an anode with tapered vanes and center strapping and had performed some preliminary testing that was very helpful in getting the new work effort off to a fast start. This anode is shown in Figure 2-24 together



989072

Figure 2-22. (a) Total phase shift of sixteen sections of the network described in Figure 2-21 for the D version (0.700 in. long anode) of the QKS1875. Experimental points are shown as small circles. Computed curve of phase shift is that given by equation (4) after it has been fitted to experimental data by deriving a value of $L_s/2L$ from the data.

(b) Reentrant Space charge spokes "see" a phase shift for seventeen cavities rather than sixteen.



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Figure 2-23. Comparison of the phase shift properties of the 0.400 in. long and the 0.700 in. long slow-wave structures utilized in QKS1875A, B, C and QKS1875D, respectively.

C-2

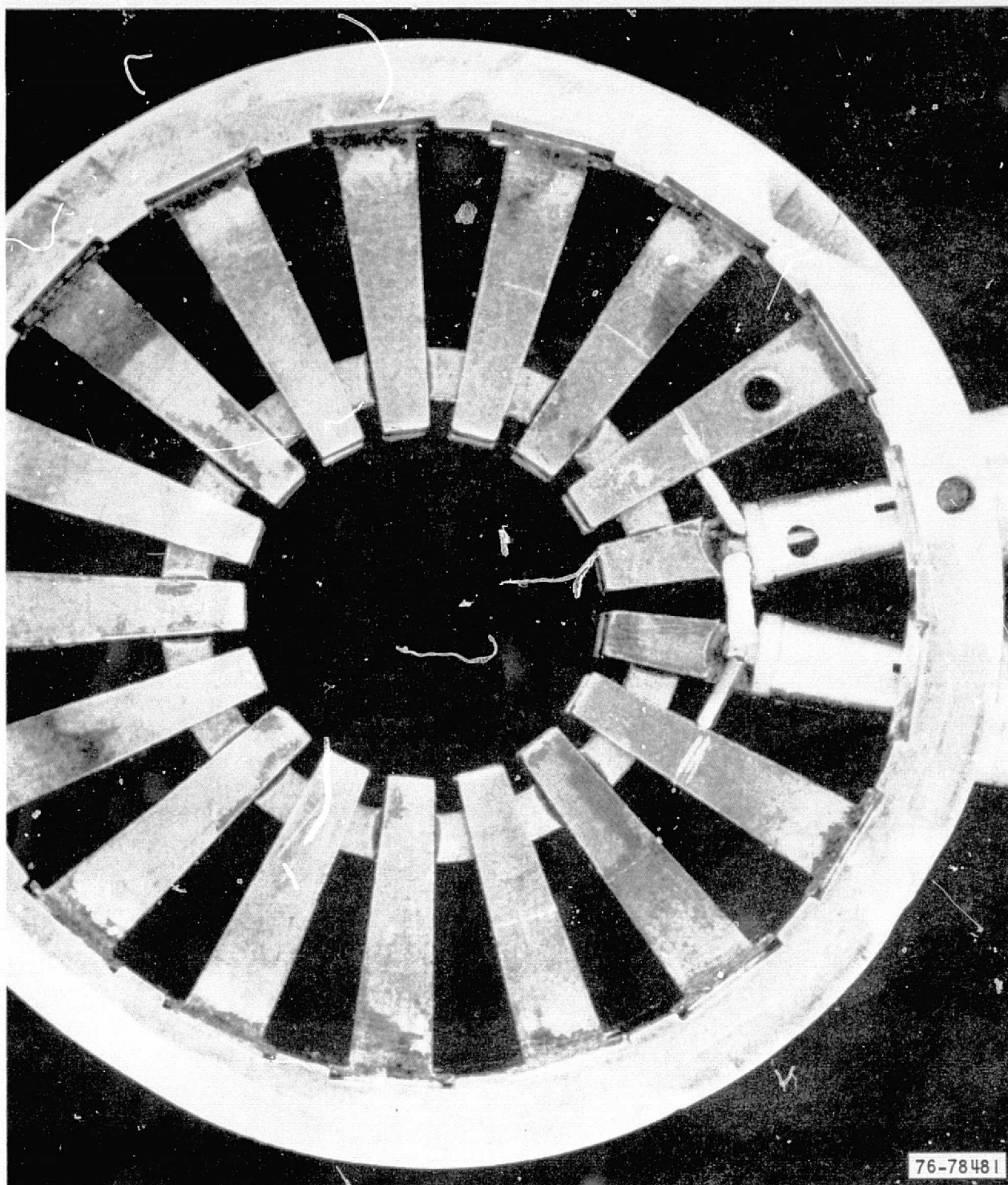


Figure 2-24. Anode constructed according to earlier baseline design. The design is basically sound electrically and for outward flow of heat from vane tips. High cost of construction and a question of making and inspecting for sound electrical contacts caused this design to be set aside in favor of the design shown in Figure 2-16. Note connections to input and output for cold-test purposes and how poor these connections are for the power and heat dissipation requirements of the space tube.

with a matching method that is electrically sound but that is hopelessly incapable of handling appreciable power levels.

Despite the apparent electrical soundness of the center-strapped tapered-vane approach, a decision was made not to use this construction because of the mechanical problem of getting the vane tips brazed together where they joined each other at the center of the anode. The critical nature of this from an electrical point of view was discovered in cold testing the anode. The tapered vane does conduct more heat than the non-tapered vane that was chosen and it is probable that it should be considered along with other items at some future time.

2.4.3 Design of Interaction Area of Tube to Provide Voltage, Current, Magnetic Field Relationships as Function of Number of Space Charge Spokes

The Amplitron obeys the relationships between applied magnetic field and operating voltage that have been established for the magnetron. (31) This relationship is based upon the physical dimensions of the anode and cathode and the number of space charge spokes that are established in the interaction area.

The voltage at which current is first initiated in the magnetron (or Amplitron) is called the Hartree Voltage, V_H . The Hartree Voltage is given by:

$$V_H = V_o \left(\frac{2B}{B_o} - 1 \right) \quad (6)$$

where B is the applied magnetic field in the interaction area and V_o and B_o are constants defined as follows:

$$B_o = \frac{21,200}{n\lambda \left(1 - \frac{r_c^2}{r_a^2} \right)} \quad \text{gauss} \quad (7)$$

$$V_o = 253,000 \left(\frac{2\pi r_a}{n\lambda} \right)^2 \quad \text{volts} \quad (8)$$

where:

n = number of spokes of space charge
 λ = wavelength of operation in centimeters
 r_c = radius of cathode in centimeters
 r_a = radius of anode in centimeters

This diameters of the cathode and the anode in all QKS1875's constructed were 1.270 cm. and 1.992 cm., respectively. With these values inserted the expressions become:

$$B_o = \frac{21,200}{n\lambda \left\{ 1 - \left(\frac{0.635}{0.996} \right)^2 \right\}} = \frac{35,718}{n\lambda} \text{ gauss} \quad (9)$$

$$V_o = 253,000 \left(\frac{2\pi \times 0.996}{n\lambda} \right)^2 = \frac{9.898 \times 10^6}{(n\lambda)^2} \text{ volts} \quad (10)$$

The tube was designed to operate in the backward wave 180° mode so that the synchronism condition with this mode defines the number of space charge spokes, n , to be 8. It is also possible for the tube to operate in the forward wave mode by changing the direction of the magnetic field in which case the number of spokes of space charge will be 9.

If we assume 8 spokes of space charge and a wavelength of 12.24 cm (2.45 GHz), B_o is 364.9 gauss and V_o is 1031 volts. The relationship between the predicted operating voltage V_H and magnetic field B is given by equation (6). The corresponding curve on Figure 2-25 is marked "n=8, 2450 MHz, B.W." If we assume 9 spokes of space charge, the relationship is as shown on curve marked "n=9, 2450 MHz, F.W."

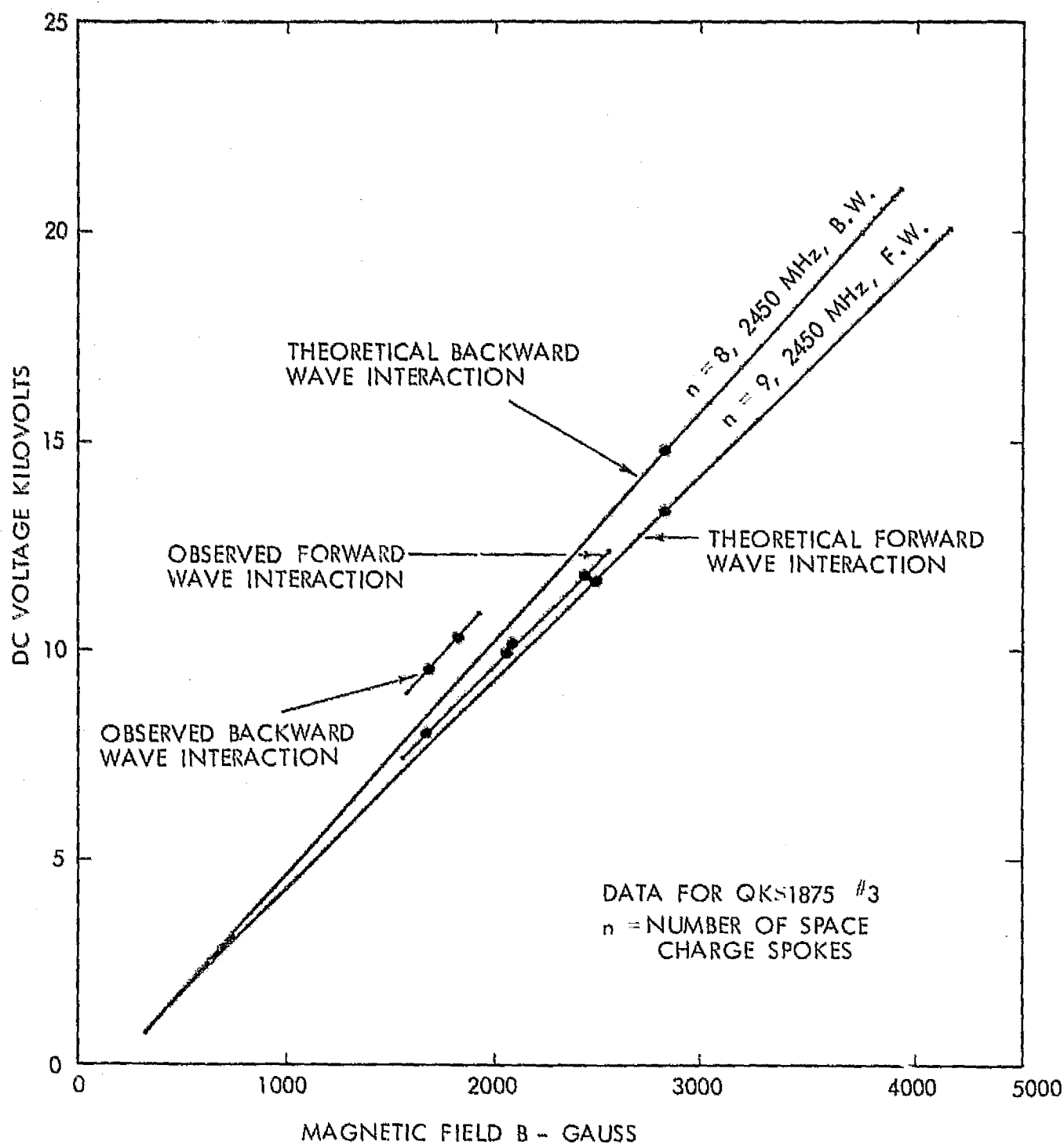
As is shown on Figure 2-25 operation was obtained in both the forward wave mode and backward wave mode of interaction at the voltage levels shown. This is discussed in Section 2.5.4.

It may also be possible for the tube to operate with a phase shift of the order of 540° around the circuit in either the forward wave or backward wave mode. The frequency here corresponds to about 4000 MHz as seen in the phase shift characteristics shown in Figure 2-23. At a given value of applied magnetic field the interaction will occur at much higher voltages. However, if for some reason current flow were initiated at a high voltage, and there were high impedance mismatches at the frequency corresponding to the 540° mode, the tube could oscillate at this frequency.

The possible competition between forward and backward wave modes of interaction at a given magnetic field and anode voltage is clarified by means of the $\omega\beta$ diagram as discussed in the next section.

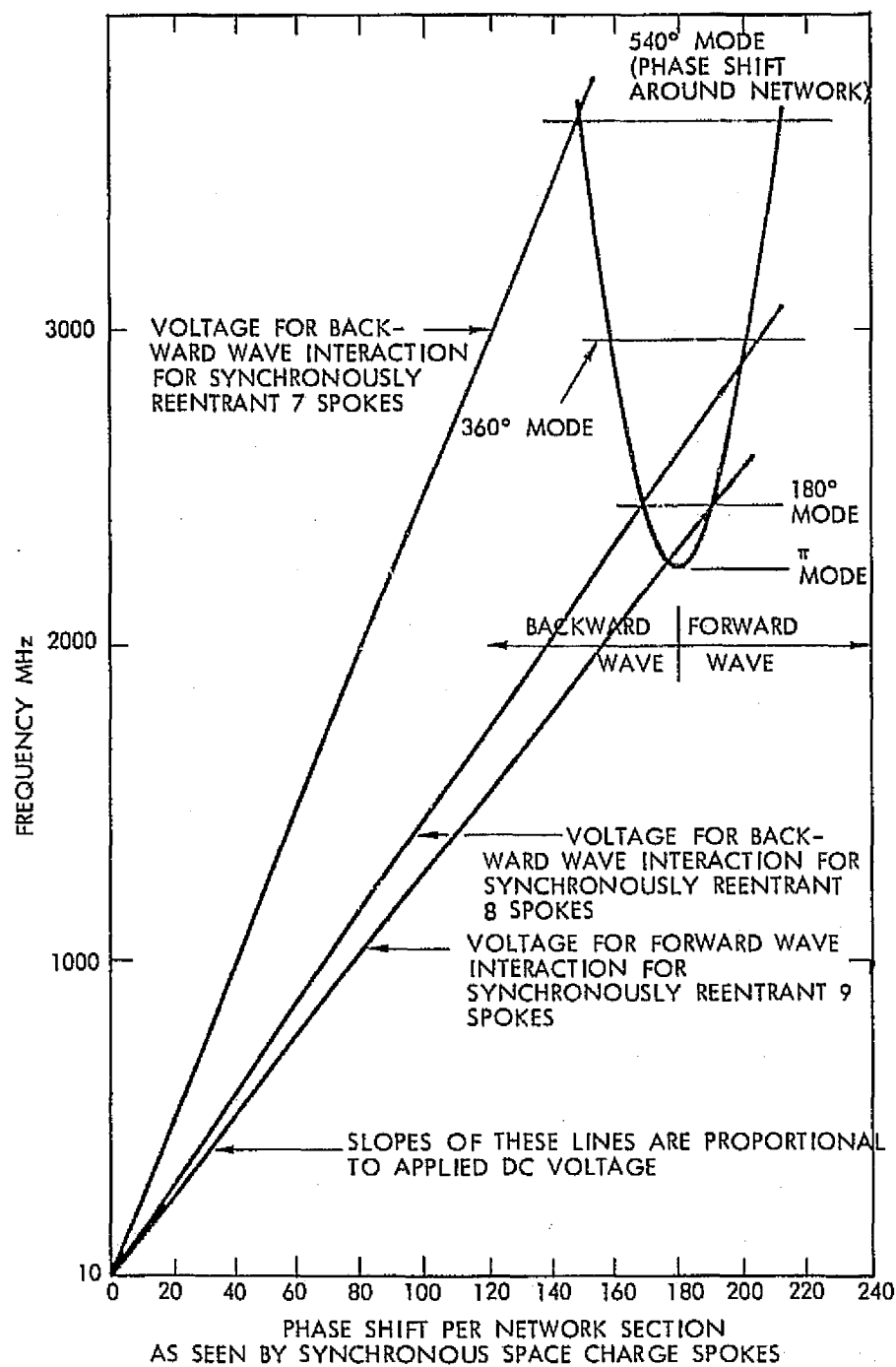
2.4.4 Superposition of Slow-Wave Structure and Interaction Area Parameters to Define Operating Characteristics $\omega\beta$ Diagram

Figure 2-26 is the so-called $\omega\beta$ diagram in which frequency is plotted against phase shift per network section as seen by the synchronous space charge spokes. The convention in plotting these diagrams is to show backward wave interaction and forward wave interaction as a continuous curve joining at the point of 180° phase shift per network section. Actually, backward



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Figure 2-25. Operating potential V_H as a function of applied magnetic field for principal forward and backward wave modes of interaction in the QKS1875. The QKS1875C design exhibited both forward wave and backward wave interaction as shown by the experimental data.



989066

Figure 2-26. $\omega\beta$ diagram for the QKS1875. Explanation of the diagram is given in the text.

wave interaction should be associated with negative values of phase shift and would be the mirror image to that shown in Figure 2-26 and would be located on the other side of the abscissae axis.

If the microwave drive is inserted at a given port of the Amplitron it will be necessary to change the direction of magnetic field to go from forward to backward wave amplification or vice versa. However, the tube may oscillate by itself without any microwave drive and under these circumstances the tube itself will select forward or backward wave mode of interaction regardless of an arbitrary definition of which is the input port of the device. There can also be competition between self oscillation and operation as an amplifier in which operation is locked to the frequency of the driver. The high impedance of the circuit near the lower cutoff frequency of the network makes self oscillation near that frequency of concern, but oscillation is discouraged by the odd number of vanes which requires that the space charge spokes suddenly shift their position to remain in synchronism as they cross from output to input.

A further study of Figure 2-26 will make more clear the other possible modes of interaction. For example, if the magnetic field is in the direction to provide backward wave interaction with the drive signal set at 2.45 GHz then the applied voltage is also that required for forward wave interaction at 2900 MHz. However, the reentrant space charge spokes will again be out of phase, thus discouraging self oscillation at this frequency.

2.5 Experimental Results and Test Data

2.5.1 Introduction

The experimental results have been most encouraging in some aspects and disappointing in others. They have been very encouraging in the indication of high signal to noise ratio and of course, one of the major purposes in initiating the first phase of the multiphase program was to obtain such noise measurements to help resolve an area of doubt about the signal to noise performance of Amplitrons.

The experimental results have been disappointing in the area of overall efficiency where the maximum efficiency achieved has been only 70%. And they have been most disappointing in the area of gain and operating power level. The low efficiency is not all conclusive, however, because it is known from other historical data that Amplitron efficiency can be well above 80% as discussed in Section 1.3.3. The observation of low gain and relatively low upper boundary on microwave power output was unexpected. The cause of this is believed to be a combination of a short anode length and an unusual microwave field pattern in the interaction area which allows the break up of the spoke of space charge as it passes from the output of the device to the input of the device. This is discussed in considerable detail in Section 2.7. It is also probable that the field pattern is the most serious reason for the low efficiency.

However, in those aspects of tube design which are essential for obtaining the very high efficiencies eventually anticipated for the device, two results were very encouraging. The first of these is the low insertion loss, or alternatively, the very high circuit efficiency of the device which was measured to be over 97%. The second of these is the very low leakage of space charge out of the interaction area which means that the tube should be capable of operating at high efficiency at very low values of current. Indeed it was found that the tube had essentially the same efficiency at very low power levels that it had at the maximum power level to which it was pushed.

It was not possible to obtain cathode emission from a cold cathode, at least in the proper mode of interaction, with the injection of microwave power alone. It is possible that this failure was caused by the poor field pattern since other CW Amplitrons have been successfully started with microwave drive levels considerably below those used with this tube. (See Section 1.3.2) The major impact of this finding on the first design was to change the direction of the tube design, first toward the use of a halo starting cathode which had been used successfully with other tubes. When this change did not solve the starting problem on the QKS1875 tube, the design was changed to utilize a thermionic emitting cathode which did make operation possible.

Because of the expenditure of much of the program effort upon aspects leading up to the test portion and because of substantial changes in tube design and construction in response to the test data on the first tube, it was possible to obtain only a limited amount of test information.

All of the test information presented in this section was obtained from the QKS1875C design, with the exception of some of the circuit efficiency information which was obtained on QKS1875D. QKS1875D was still under evaluation at the end of the work effort. The QKS1875C design varied from the baseline QKS1875A design in that it had a thermionic emitting tungsten helix for a cathode, had conventional end shields in addition to cathode-potential pole pieces, and a 0.200 in. increase in the magnetic field gap in the tube.

Section 2.6 deals with the various changes that were made in the A, B, C and D designs and the reasons for them.

The discussion of the test results in this section is organized as follows:

- 2.5.2 Signal to Noise Ratio Measurements and Discussion of Results
- 2.5.3 Operating Voltage and Microwave Power Output as Function of Input Current at a Fixed Magnetic Field.
- 2.5.4 Comparison of Experimentally Observed and Theoretically Derived Relationships of Operating Voltage as a Function of Magnetic Field.

- 2.5.5 Circuit Efficiency Measurements
- 2.5.6 Maximum Overall Efficiency
- 2.5.7 Gain and Operating Power Level
- 2.5.2 Signal to Noise Ratio Measurements and Discussion of Results
- 2.5.2.1 Introduction

In the judgment of many people the most important measurement to be obtained on the QKS1875 Amplitron was the amount of random and spurious noise outside of the 2400 - 2500 MHz band. There had been no historical data on this kind of noise for CW Amplitrons. A small amount of data on pulsed Amplitrons indicated a moderate rather than a low level of noise but the applicability of the data to the tube design needed for the SPS was questionable. (28)

There was other information, (22) on close-in signal-to-noise ratio on a CW Amplitron in an oscillator format that indicated a very good signal to noise ratio, but this was only suggestive that the out-of-band noise would also be low.

Because magnetrons and amplitrons are so closely related in their energy exchange mechanisms, it was logical to look to the history of signal-to-noise performance on magnetrons for additional insight. But here the observations were mixed. While CW magnetrons have been used successfully for many years in CW radar where close-in noise is important, there was a certain criticality of cathode processing that was objectionable and in any event there was no data on out-of-band noise levels.

More recently it has been discovered that the common microwave oven magnetron, now manufactured by the millions and reputed throughout the industry to be a noisy tube and manufactured with a costly addition of filters, can be converted into an extremely quiet tube by the expedient of removing heater power from the filament and operating the tube on a low-ripple DC power supply. In many ways, this discovery was a breakthrough in indicating that the basic interaction mechanism of the reentrant beam crossed field device was quiet and that spurious noise in this example had probably been spurious emission of current from the end shields of the cathode when it reached a critical temperature.

2.5.2.2 Test Results

The performance that has been observed indicates a noise power in a one megahertz band in the frequency region of 1450 to 3450 MHz that is at least 69 dB below the power level of the carrier as observed in the spectrum analyzer that was coupled to the output system through a loop in the side wall of the output waveguide. Measurements of higher ratios were prevented by the dynamic range of the analyzer.

The measurements that were made are shown in Figure 2-27. The bottom photograph, which shows the noise level over a band from 1450 to 3450 GHz, is the one of greatest interest in the SPS application. The carrier level is 70 dB above the peak of the residual noise level of the analyzer. After taking into consideration the rms value of the residual noise (taken to be 9 dB below the peak noise), and the 100 KHz bandwidth of the I.F. used in taking the data, the ratio of signal to noise for any one megahertz in the 1450 to 3450 MHz band is 69 dB.

The center photograph of Figure 2-27, taken without signal input to the analyzer, indicates that the residual noise level in the bottom photograph is caused by the analyzer noise level.

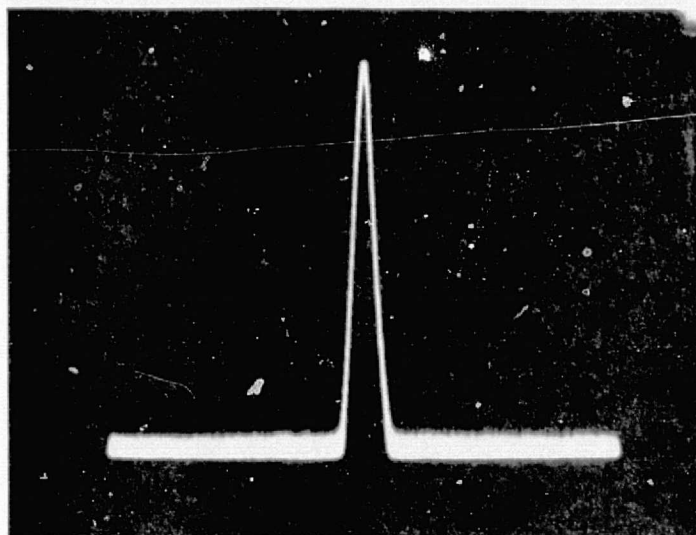
The top photograph in Figure 2-27 gives a rough indication that the close-in noise level is also low. If close-in noise were strong it would be observed on the skirts of the carrier near the base line. The fact that the carrier response disappears cleanly into the residual noise of the spectrum analyzer indicates low close-in noise.

2.5.2.3 Discussion of Test Results

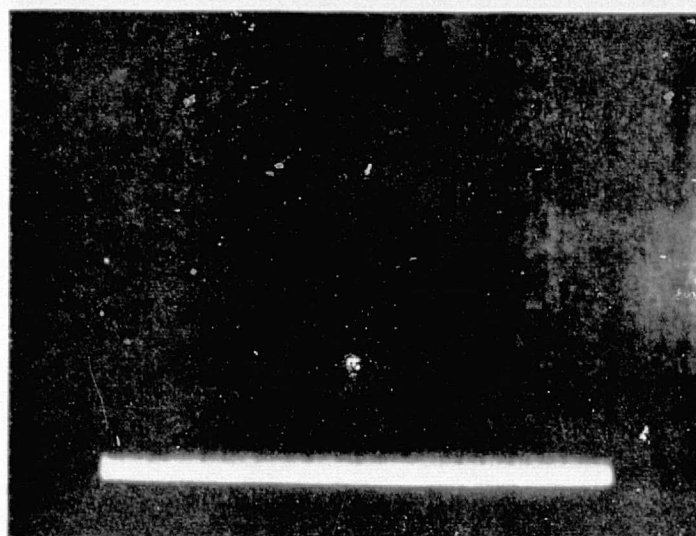
The results that have been obtained on signal to noise ratio are very encouraging but more noise measurements need to be made with a high Q "notch" filter centered at the carrier frequency to allow the insertion of a signal level approximately 50 dB above that now permitted by the dynamic range of the analyzer. Measurements of this type which were made on the microwave oven magnetron run without any power on the filament (other than backbombardment power), have indicated signal to noise ratios as high as 115 dB per MHz of random noise outside of the 100 MHz guard band. As shown in Figure 2-28 this level of random noise, assuming the radiated noise from the satellite is spread over a hemisphere is 55 dB better than would be required to meet the current CCIR requirement of $154 \text{ dBW/M}^2/4 \text{ KHz}$. Since the Amplitron and magnetron employ the same energy conversion principle, there is reason to believe that the actual signal to noise ratio of the Amplitron is in the same region. Meanwhile the 69 dB/MHz signal-to-noise ratio marginally meets the CCIR requirements under the same assumption of hemispherical radiation.

While the energy exchange mechanism in the magnetron and amplitron are essentially the same, there are different circuit arrangements which may make them behave differently with respect to noise that is close to the carrier, with the prognosis in favor of the Amplitron. The magnetron has a reentrant circuit which allows noise energy close to the carrier frequency to propagate around the circuit and be reinforced by interaction with the electron beam. A well-matched Amplitron circuit, on the other hand, forces any noise energy on the circuit to be absorbed in the output or input. The "stabilotron" device (32) which is an oscillator version of the Amplitron takes advantage of this failure to build up noise oscillations under well matched conditions by

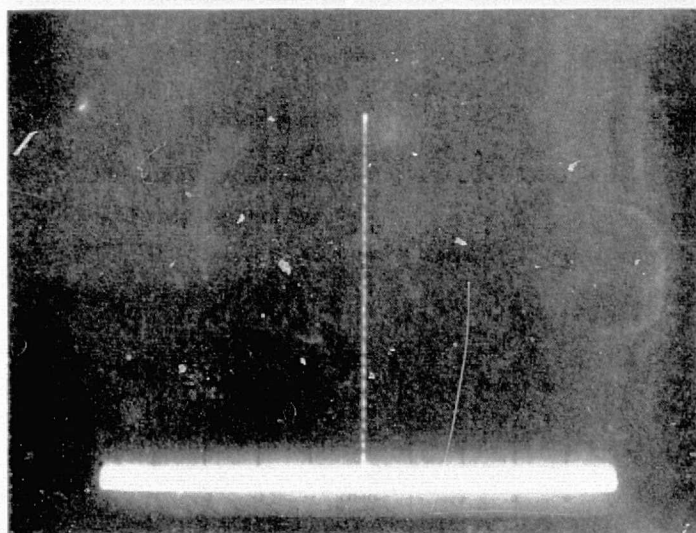
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OF POOR QUALITY



"Near-in" spectrum of QKS 1875 No. 3 Amplitron. Total sweep is 2447 MHz ± 5 MHz. I.F. BW = 100 KHz. Peak of carrier is 75 dB above base line.



Residual Noise level of HP Spectrum Analyzer over 1450 to 4450 MHz sweep. I.F. BW = 100 KHz.



Output of QKS 1875 No. 3 Amplitron over band of 1450 to 4450 MHz. The carrier is 75 dB above the base line. Only noise visible is residual noise of spectrum analyzer. I.F. BW = 100 KHz.

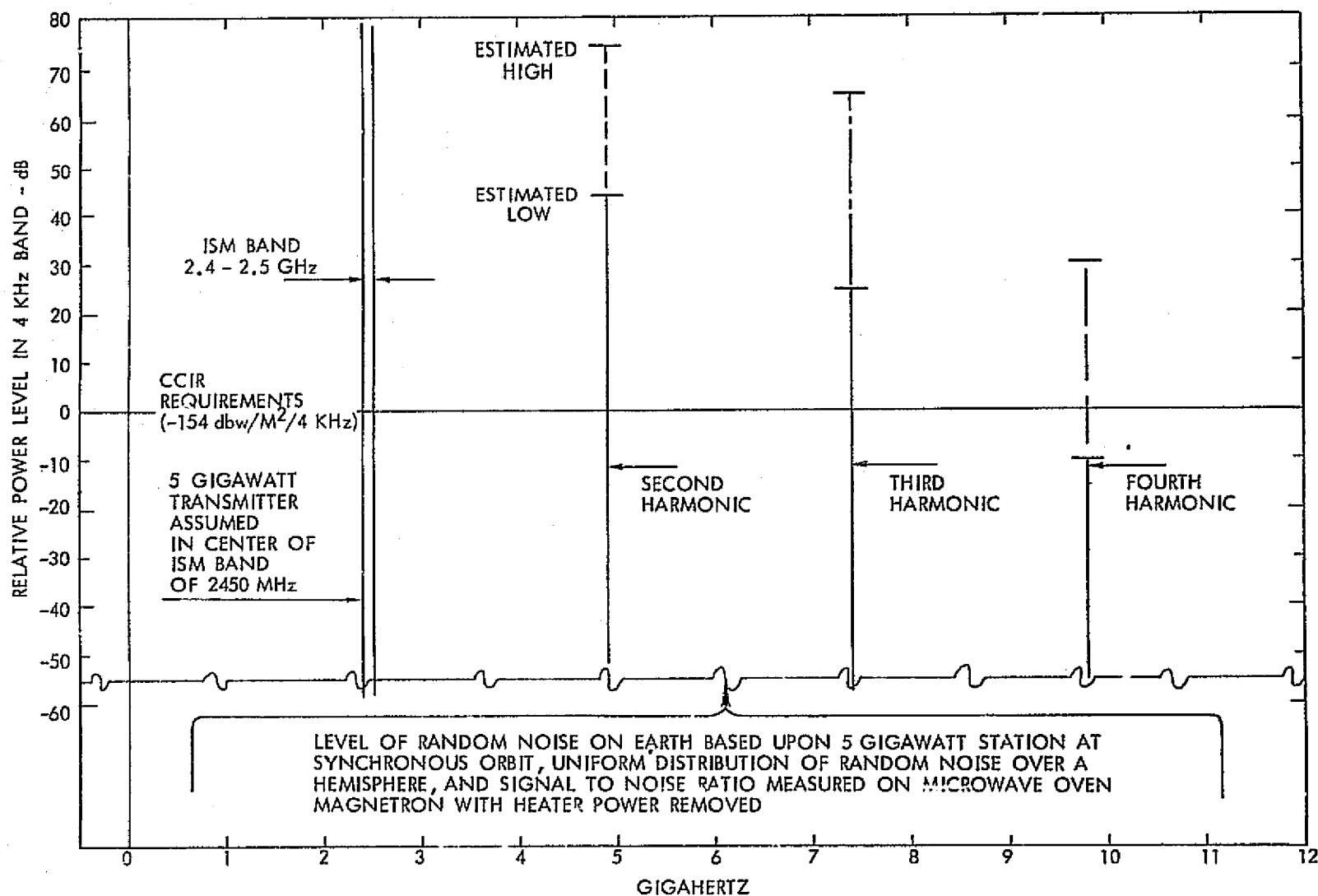
CW power output - 1017 watts

CW power added - 540 watts

Efficiency = $\frac{\text{CW power added}}{\text{DC power in}}$ = 63.9%

A CW magnetron is the driver

Figure 2-27. Noise measured in the QKS1875C Amplitron. Limitation on measurement of noise level was the residual noise level of the spectrum analyzer.



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Figure 2-28. Relative levels of noise requirements and behavior of selected microwave generators in the SPS system. The microwave oven magnetron has exhibited very low levels of noise. The QKS1875 Amplitron noise measurements, limited by the sensitivity of the measuring equipment are at approximately the 0 db level. The actual Amplitron noise is expected to be close to magnetron noise level when measurements are made with the sensitive test equipment used on the magnetron.

matching one of the outputs, except for the interposition of a high Q cavity which reflects power over a very narrow frequency region. The resulting signal at the resonant frequency of the cavity is very clean.

Now, if we look for an analagous selective action in the device when used as an amplifier, it is found that the drive frequency of an external signal replaces the reflection from a hypothetical cavity that reflects at only one frequency, rather than a narrow band of frequencies around the resonant frequency of the cavity as in the "stabilotron". This analogy would suggest that a well matched Amplitron should have a very high signal to noise ratio around the drive frequency. Moreover, the Amplitron does not need to be well matched at frequencies far away from the drive frequency because the synchronous conditions for interaction do not exist-that is, the noise at other frequencies needs different value of applied voltage as shown in the $\omega\beta$ diagram of Figure 2-26.

The noise measurements that were made on the QKS1875C Amplitron were made at operating efficiencies in the range of 63 to 67% and with a power output level of one kilowatt. The output level was low because of the tube's inability to operate at appreciably higher power levels, a subject discussed elsewhere. The general observation on close-in signal-to-noise ratio performance of crossed field devices is that it usually improves with both efficiency and power level.

It should not be concluded that the signal to noise performance indicated by Figure 2-27 is always the noise performance observed on the QKS1875C but rather that it seemed to be a state of operation that did not require critical adjustment of operating parameters. However, other operating conditions were found in which the carrier seemed to be phase modulated so that a line spectrum 40 to 50 dB below and around the carrier, with the lines being separated by about 10 MHz, were observed. There are apparently a number of different operating modes in a non-optimized tube that should be examined to reveal the causative mechanisms.

2.5.2.4 Conclusions

Good signal to noise ratio performance was observed in QKS1875C but these results should be put into perspective by indicating that they were obtained from probably the first noise measurements of any kind that have been made on CW Amplitrons in a decade, and the first measurements ever to check random noise over a broad frequency region. During the last decade noise measuring instrumentation has greatly improved and it is expected that a dedicated effort to study and observe noise on an experimental basis can produce rich results. A substantial engineering effort is probably necessary to identify and remove the ancillary noise producing mechanisms that exist in this device and which obscure what is probably a basically quiet energy exchange process.

2.5.3 Operating Voltage and Microwave Power Output as Function of Input Current at a Fixed Magnetic Field.

One of the successes of this development has been the achievement of very low leakage current from the interaction area between the cathode and anode prior to the onset of interaction between the beam and the slow wave circuit. This low leakage current results in a very sharp "knee" on the voltage current characteristic and enables the tube to perform well at very low values of anode current. It may be recalled that one of the reasons for setting the upper voltage rating on this tube at 20 kilovolts was the fear that leakage current could detract from the operating efficiency at operating levels of as much as two or three kilowatts. The data that we have obtained indicates that the full efficiency of the tube can be obtained at operating levels of two hundred watts or so.

One of the interesting results of this achievement is that the design could be scaled with confidence to 40 kilovolt and 10 to 20 kilowatts of output, -if leakage current were the only consideration.

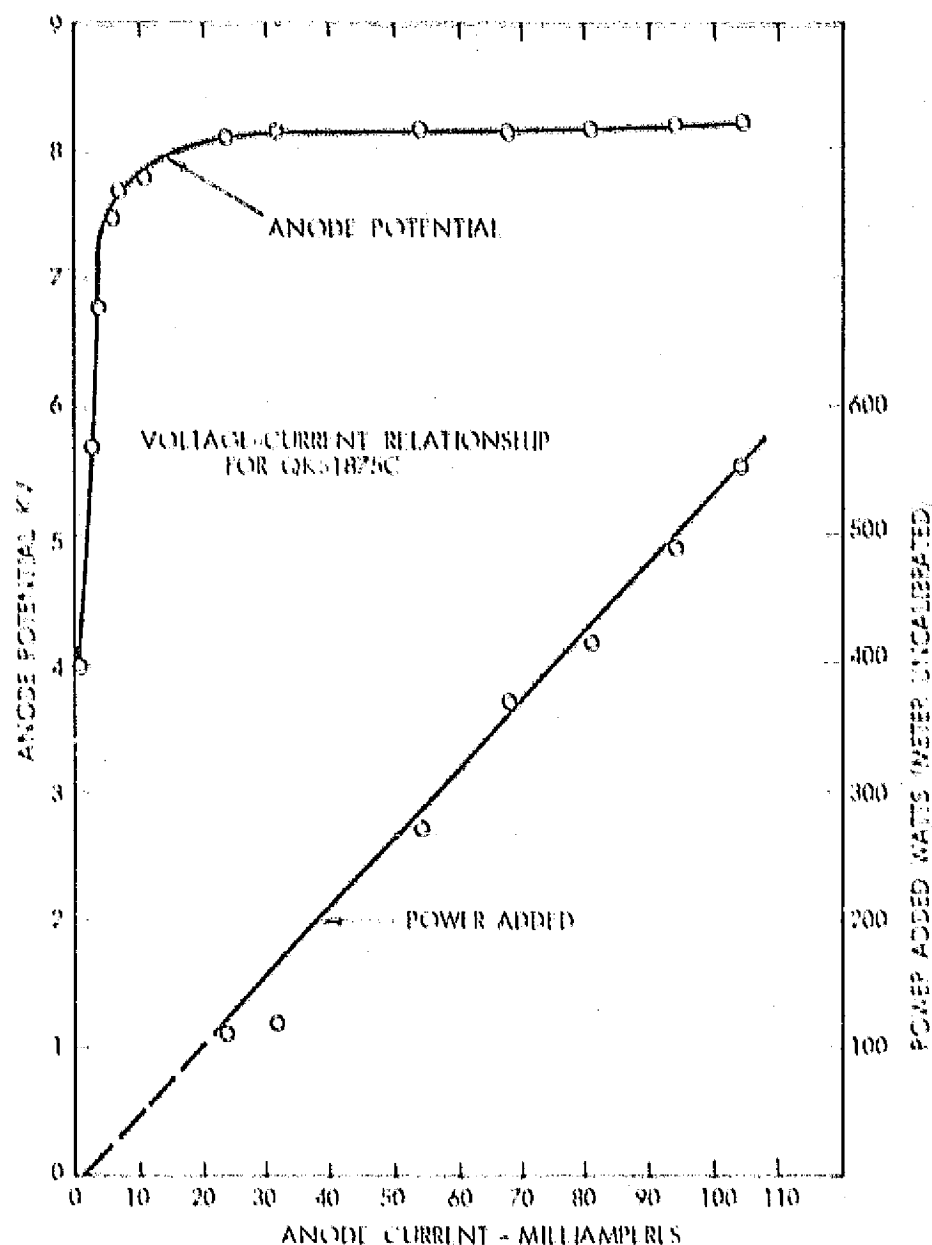
The performance that has been achieved is illustrated by Figures 2-29 and 2-30. Figure 2-29 shows the anode potential and the microwave power added by the Amplitron as a function of current up to 110 milliamperes, while Figure 2-30 shows the same data on a scale which includes the design operating point for the anode current. The data indicates that good efficiency is achieved at a value of power output which is only two to three percent of the rated power level. It follows that the tube has a very wide range of power level over which good efficiency can be achieved.

2.5.4 Comparison of Experimentally Observed and Theoretically Derived Relationships of Operating Voltage as a Function of Magnetic Field.

The theoretical relationship for the DC voltage at which interaction starts (Hartree voltage) as a function of magnetic field was given in Section 2.4.3. The corresponding experimental data along with the predicted curve is given in Figure 2-25.

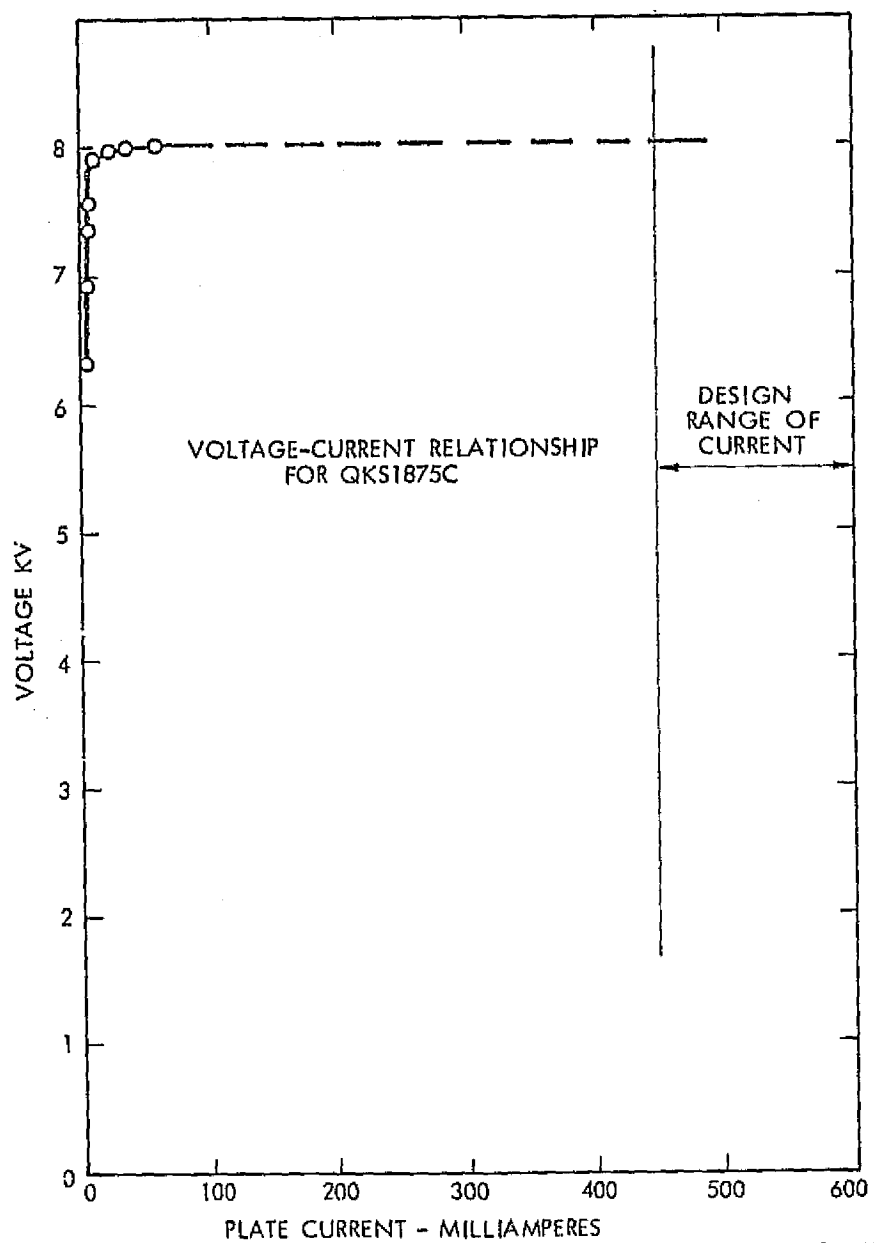
The agreement between the experimentally observed and predicted values is quite good, considering that there are tolerances involved in tube dimensions and in calibrating the magnetic field. The magnetic field measurements are made on the axis of the cathode while the magnetic field in the interaction area is off center. The end shields on the cathode may also have a shielding action with respect to the DC electric field between cathode and anode.

The operating and theoretical curves in Figure 2-25 should be studied in association with the $\omega\beta$ diagram given in Figure 2.26.



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Figure 2-29. (a) The voltage-current characteristic of the QKS1875C showing the sharp "knee" which is needed for low power operation, and (b) "microwave power added" as a function of current showing that the operation begins at very low power levels and that the efficiency at the low power levels is comparable to that at the higher power levels.



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Figure 2-30. Voltage-current characteristic for the QKS1875C showing a very sharp "Knee" at a value of anode current that is a very small fraction of the normal operating value of anode current.

The circuit efficiency becomes a very important factor in the space tube as the overall efficiency of the tube is improved. A relatively short slow wave structure of the vane and strap configuration has a potentially low loss, and this low loss is reduced even further if the tube is run with appreciable gain because the power that is added toward the output of the tube does not have to flow in the first part of the circuit. The decrease in loss for this reason approximately cancels out the additional losses in the copper because of the elevated temperature at which the tube will be run.

A measurement of insertion loss or circuit efficiency of the Amplitron slow wave circuit was made by injecting a substantial amount of microwave power into the tube and noting the power dissipated in the tube relative to the power measured in the output load connected to the tube, both by thermal means. Since the cooling jacket for the anode of the tube and the water load are connected in series with respect to the water flow, the ratio of the temperature rise within the tube and within the water load is a good measurement of the inefficiency. This turned out to be $.025 \pm .003$, so that the cold circuit efficiency is $97.5\% \pm .3\%$. These measurements were made on the slow wave circuit of QKS1875D which had the longer 0.700 in. anode.

Measurements made in this manner do not include the losses in the output window of the Amplitron or in the coaxial-to-waveguide transition units. However, a set of careful measurements which did include these losses were made on QKS1875C.

These measurements were made in such a manner as to eliminate the need for accurately calibrating the power meters; only the preservation of the sensitivity of the input and output power meters over a matter of 30 minutes or so was needed. The procedure was to first note the readings on the input and output power meters with a dummy section of waveguide inserted into the position that would normally be occupied by the Amplitron. The dummy section of waveguide was then removed and the Amplitron inserted into the same location. A second set of readings was then made on the input and output power meters. By comparing these measurements an accurate measurement of the insertion loss of the Amplitron complete with its waveguide transitions could be made. To eliminate the impact of reflected power upon the measurements, any reflected power when the dummy section of waveguide was used was removed by trimming the match into the water load, and any reflected power when the Amplitron was inserted was removed by adjusting the trimming screws provided in the waveguide transition for that purpose. High confidence in reducing the reflected power to a negligible level was obtained with the use of a precision moveable-probe type waveguide VSWR detector. The frequency was also kept constant throughout the set of measurements.

The ratio of the readings on the power meters for the set of measurements with the dummy waveguide section present was 1.036 while the

ratio of the readings on the power meters for the set of measurements with the Amplitron in position was 0.993. A comparison of these ratios indicates a 4.4% insertion loss after allowing a calculated insertion loss of 0.1% for the dummy section of waveguide.

The difference in the two sets of measurements was roughly 2%, indicating losses beyond the Amplitron itself of 2%. Only a small fraction of these additional losses should occur in the space environment because the tube will be connected directly to the waveguide without the intervention of the vacuum windows which together with the sliding contacts and relatively poor joints existing in the present arrangement account for probably 80% of the additional loss.

2.5.6 Maximum Efficiency Achieved

Table 2-1 provides several examples of overall efficiency together with the gain, magnetic field, operating voltage, and output power level for that value of efficiency. Two efficiencies are given. The first is the initially measured efficiency and the second is the true efficiency of the Amplitron after proper adjustments have been made for power generated but reflected and not measured in the output, DC power leakage losses in the cathode cooling water, and microwave plumbing not permanently attached to the Amplitron.

The true efficiency of the Amplitron is the conventional expression for Amplitron efficiency:

$$\text{Efficiency} = \frac{\text{Microwave power output} - \text{Microwave power input}}{\text{DC Power Input to the Amplitron}}$$

The initial efficiency measurements were made according to the following expression:

$$\text{Initial Efficiency Measurement} =$$

$$\frac{\text{Microwave Power measured in Water Load} - \text{Microwave Power Input}}{\text{DC Power Output of the Power Supply}}$$

In the second expression the measured microwave power does not take into account the microwave power that is generated but reflected and measured as reverse directed power. This reflected power can be eliminated by trimming the output match so that all of the generated power flows into the water load, but this was not done in the efficiency examples cited. It also does not take into account the losses in the coaxial to waveguide transitions. Finally the second expression does not take into account that fraction of the dc power output of the power supply which is consumed in leakage power in the cooling water hoses to the cathode of the tube. Table 2-2 provides the correction factors for each of these items, and shows that for the last example of 65.4% efficiency in Table 2-1, the correction factor should be 1.075 to provide a true overall efficiency of the Amplitron itself of 70.2%. Similar corrections could be made

TABLE 2-1

OPERATING CHARACTERISTICS AND EFFICIENCY

Magnetic Field Level (gauss)	Operating Voltage Level	Power Out Level (watts)	Gain (db)	Initial Efficiency Measurement	Amplitron Efficiency
1700	8180	610	1.9	53%	
2000	9860	1000	3.7	63.5%	
2500	11750	1300	3.8	65.4%	70.2%

TABLE 2-2

EFFICIENCY CORRECTIONS TO INITIAL MEASUREMENTS
TO OBTAIN TRUE AMPLITRON EFFICIENCY

	Efficiency Correction Factor
Power Reflected Which Could Have Been Matched Out 30 Watts Out Of 1300 Or 2.3%	1.023
Leakage Current In Cathode Cooling Water 3 Ma Out Of 97 Or 3.2%	1.032
Waveguide To Coax Transition Loss 1.9%	1.019
Accumulative Correction Factor	1.075

for the first two efficiency examples cited.

To make the initial efficiency measurements as accurate and valid as possible the microwave power input meter with its directional coupler and the output power meter with its directional coupler were calibrated simultaneously with the basic method of measuring power output, that is, by accurately measuring the rate of flow of cooling water in the water load and the temperature rise of that water. For this calibration the Amplitron was replaced with a short section of 4.340 in. waveguide. The care used in calibrating the power measuring equipment and its use makes it possible to assign a probable error of $\pm 1\%$ to the above efficiency figures.

The efficiency measurements discussed above were made with Amplitron QKS1875C operating in the forward wave mode.

2.5.7 Gain and Operating Power Level

It has been a great surprise to find that this tube is gain and power output limited. It had been anticipated that the tube would have no difficulty in operating with a gain of 10 dB at the five kilowatt power output level. By contrast typical gains are 3.8 dB with 1300 watts out. The specific gain of 7 dB called for in the objective specifications, can be obtained at power output levels of no more than 250 watts. The probable reason for the wide disparity between predicted and experimental results and the corrections that need to be made are discussed in considerable detail in Section 2.7. In this section a brief discussion of the general relationship between the maximum available gain in an Amplitron as it is related to microwave drive level will be given.

Historically, it has been found that the relationship between the maximum available power output from an Amplitron and the power level of the microwave drive is given by the following:

$$P_o = \frac{K^2}{4} + K\sqrt{P_i} + P_i \quad (11)$$

where: K = a constant depending upon the tube design parameters

P_o = maximum microwave power output

P_i = microwave power drive level

This relationship has been found to hold over a very wide range of drive levels as shown in Figure 2-31. The data in Figure 2-31 is for the QK434 Amplitron which has been widely and successfully used for twenty or more years in "stabilotron" form. The data shown is for the QK434 operating strictly as a broad band Amplifier (22, 19).

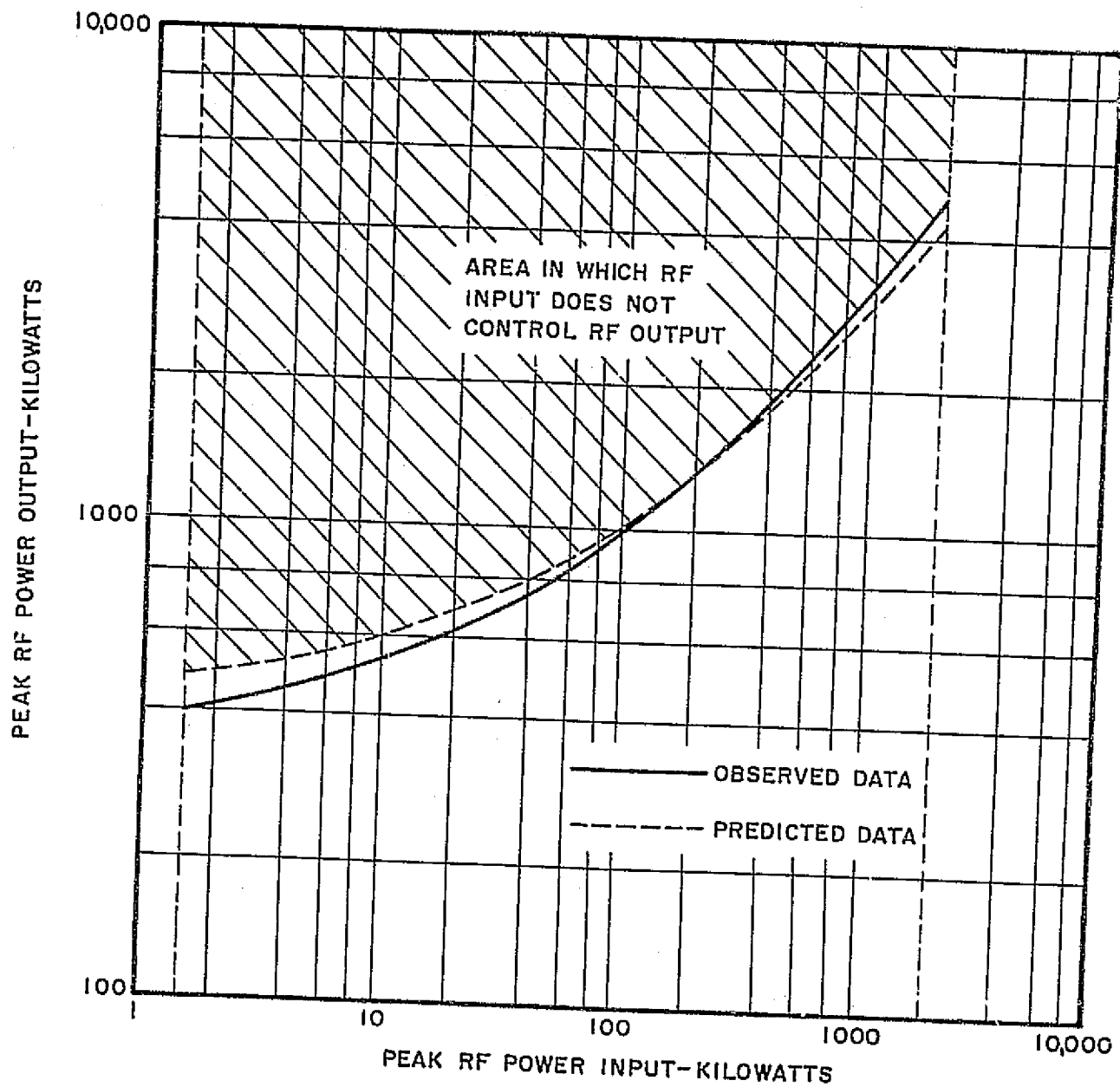


Figure 2-31. Experimental data indicating close agreement with the relationship between maximum microwave power output and the microwave drive level given by equation (11) for the QK434 Amplitron.

It follows from (11) that the maximum gain that can be obtained at any rf drive levels is:

$$\begin{aligned} \text{Maximum Gain} &= \frac{P_o}{P_i} \\ &= \frac{K^2}{4 P_i} + \frac{K}{\sqrt{P_i}} + 1 \end{aligned} \quad (12)$$

The constant K is obviously the important parameter in evaluating the maximum gain that can occur at a given drive level, and it can be readily calculated for a given tube design once the maximum power output for one representative value of drive power is known.

The relationship of equation (11) seems to hold for the QKS1875C Amplitron as indicated by Figure 2-32, where there is a close agreement between the predicted relationship, once the value of K has been computed, and the experimental data. The problem, of course, is that the value of K is so very low compared to what it should be in relationship to the K computed for the QKS1532 tube which was thought to be nearly the same electrical size tube as the QKS1875. The K value computed from Table 2-1, item 3, is 25.6 while for the QKS1532 it is 194.0.

The probable reason for this great disparity is the subject of Section 2.7.

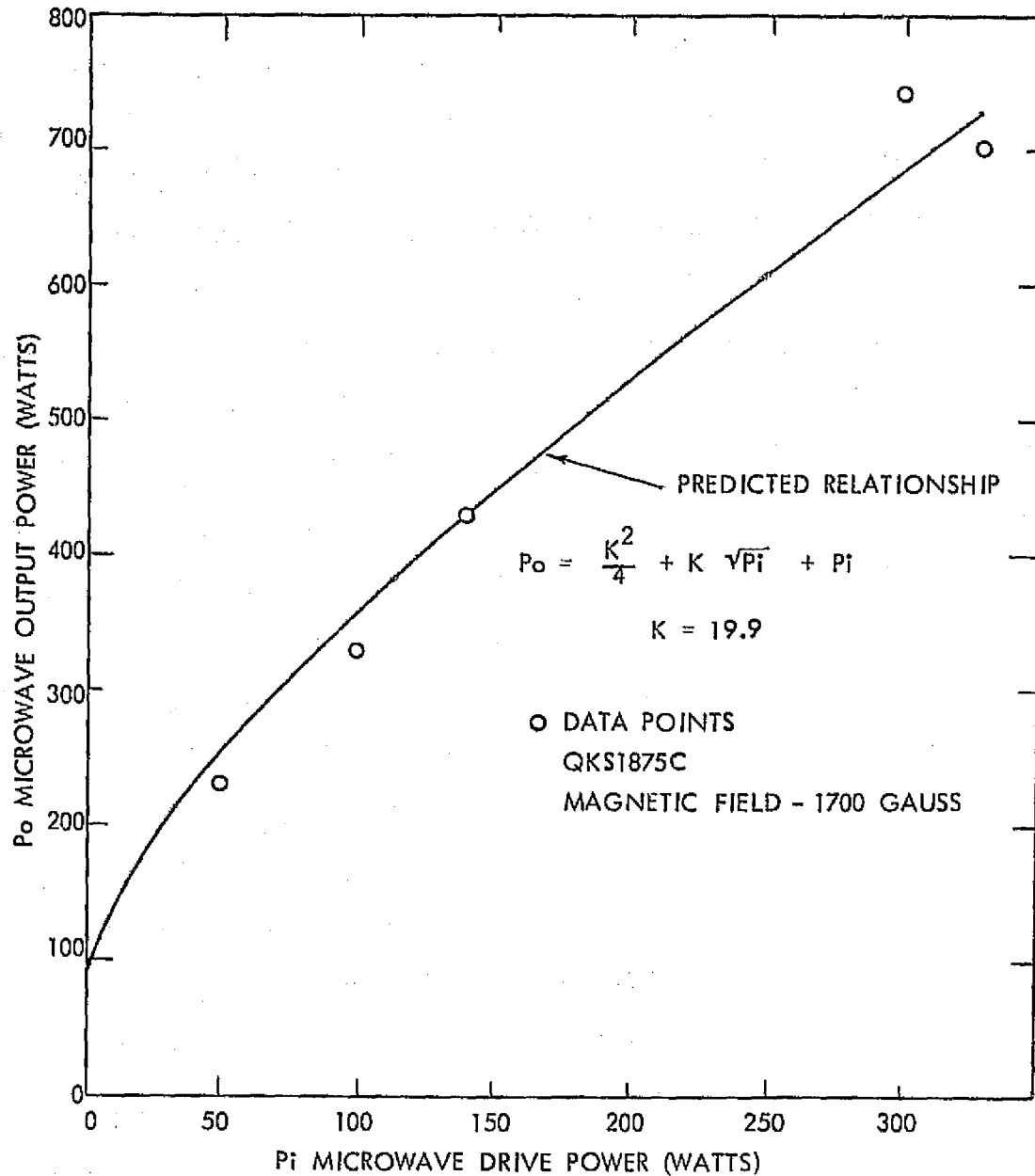
2.6 Modifications of the Baseline Design, QKS1875A, and Purpose of the Modifications

In the work effort covered by this report, there were three design modifications to the original design, making a total of four different electrical and mechanical designs that were made. This section is intended to serve as a summary of the reasons for and the nature of these modifications. The test results of each design indicated the nature of the modifications to be made to the next design.

All of the modifications involved a physical area of the tube close to the cathode-anode interaction area so that it is possible to use relatively simple drawings to indicate the changes that were made. These drawings, which are included in this section, should be used in conjunction with the cross section of the complete tube for the base line, QKS1875A drawing, Figure 2-10.

2.6.1 QKS1875B Modification Resulting From QKS1875A Test

The QKS1875A could not be started with microwave drive of up to two kilowatts. It was reasoned that either the platinum surface was badly contaminated with an overlay deposit of poor secondary emitting material or that some other phenomenon was preventing starting. Because primary-emitting halo cathodes had been successfully used in starting magnetrons with water cooled



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Figure 2-32. Experimental data indicating that the relationship between maximum microwave power output and the microwave drive level as given by equation (11) holds for the QKS1875C.

pure metal cathodes, it was reasoned that a similar arrangement might permit the buildup of gain in the QKS1875 Amplitron.

The modifications incorporated into the Amplitron baseline (QKS1875A) design to make the QKS1875B design is shown in Figure 2-33. Basically the starter halo cathode was added as shown and the pole pieces were each cut back 0.100 inch to accommodate the halo and reestablish an axially symmetric field. One side of the halo is connected to a metallic pin on the pole face while the other end is connected to an electrically insulated feed through bushing located at the center of the pole face as shown in Figure 2-33. The complete pole piece assembly was checked in a bell jar and the current and voltage-temperature relationships determined.

The starter cathode follows a design that was similar to that used on a 50 kilowatt, 915 megahertz CW magnetron with a water cooled platinum cathode. That enabled the magnetron to start from noise and build up rapidly to the desired power output level. After the magnetron had started the starter cathode was turned off.

It will be noted that in many ways such a cathode will simulate a β emitter which might take the form of titanium titrite attached to the face of the tail pole piece.

All other design aspects of the tube remained the same. In fact the test model of the QKS1875B was the QKS1875A whose tail pole piece and cathode pole piece assemblies had been removed, reoperated to accommodate the necessary changes, and then reassembled.

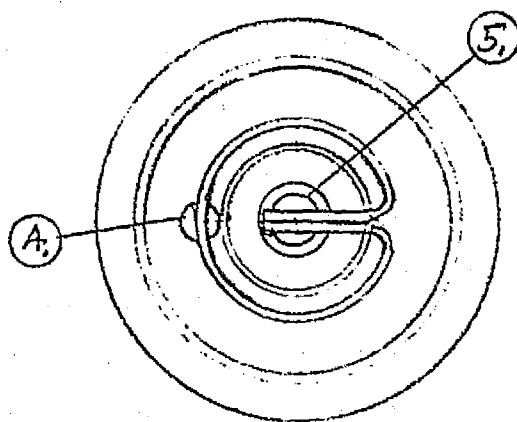
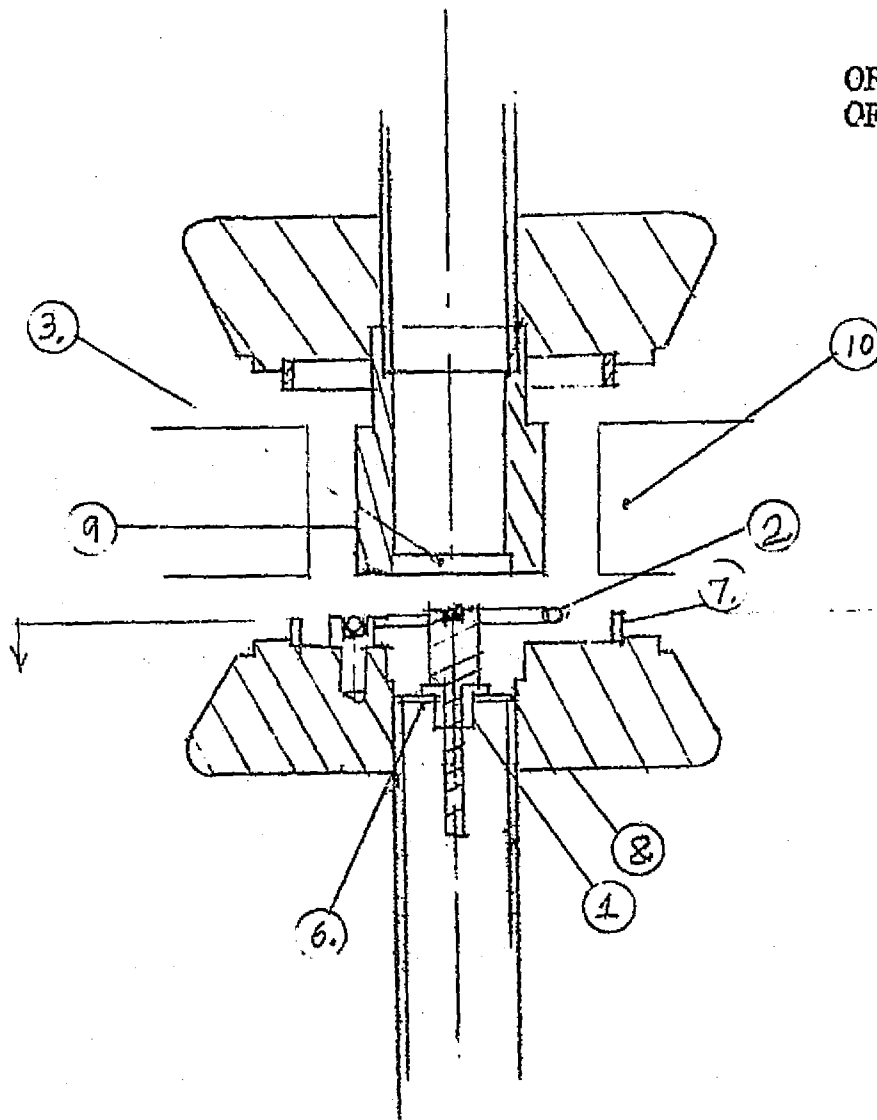
Figures 2-34 and 2-35 are photographs of the reoperated cathode and tail pole pieces.

Before QKS1875B was completed, SEM-EDAX tests were made on the platinum cathode surface of QKS1875A to see if it were contaminated with a low secondary emitting material. The body of evidence was not conclusive for contamination that would greatly reduce the secondary emission ratio. However, QKS1875B utilized a new platinum cathode that was electropolished to decrease the probability of a contaminated cathode as the source of difficulty.

2.6.2 QKS1875 Modifications Resulting from QKS1875B Test Data

The addition of the halo cathode did not result in proper tube performance. However, drawing emission from it started current flow between the pole pieces and the anode and resulted in rapid heating of the halo itself by electron bombardment. Current flow could also be initiated by the injection of microwaves at the input and the same rapid heating of the halo would result. Although the nature of the tube operation was not understood, it was clear that

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1	883106-4	Inner Pole Ext
1	883106-4	Ceramic Bu.
2	968782	Heater
3	944225	Cap
4	968785	Cupro. Pin
5	968785	Moly Pin
6	968786	Seal Disc
7	968787	Inner Pole Ext
8	968788	Pole Reop.
9	968789	Cathode Reop.
10		Anode

Figure 2-33. The modifications of the baseline design that resulted in the QKS1875B design is shown above. The major feature is the addition of a halo cathode as a starting device and the increasing of the gap between the top and bottom pole pieces by 0.200 in.

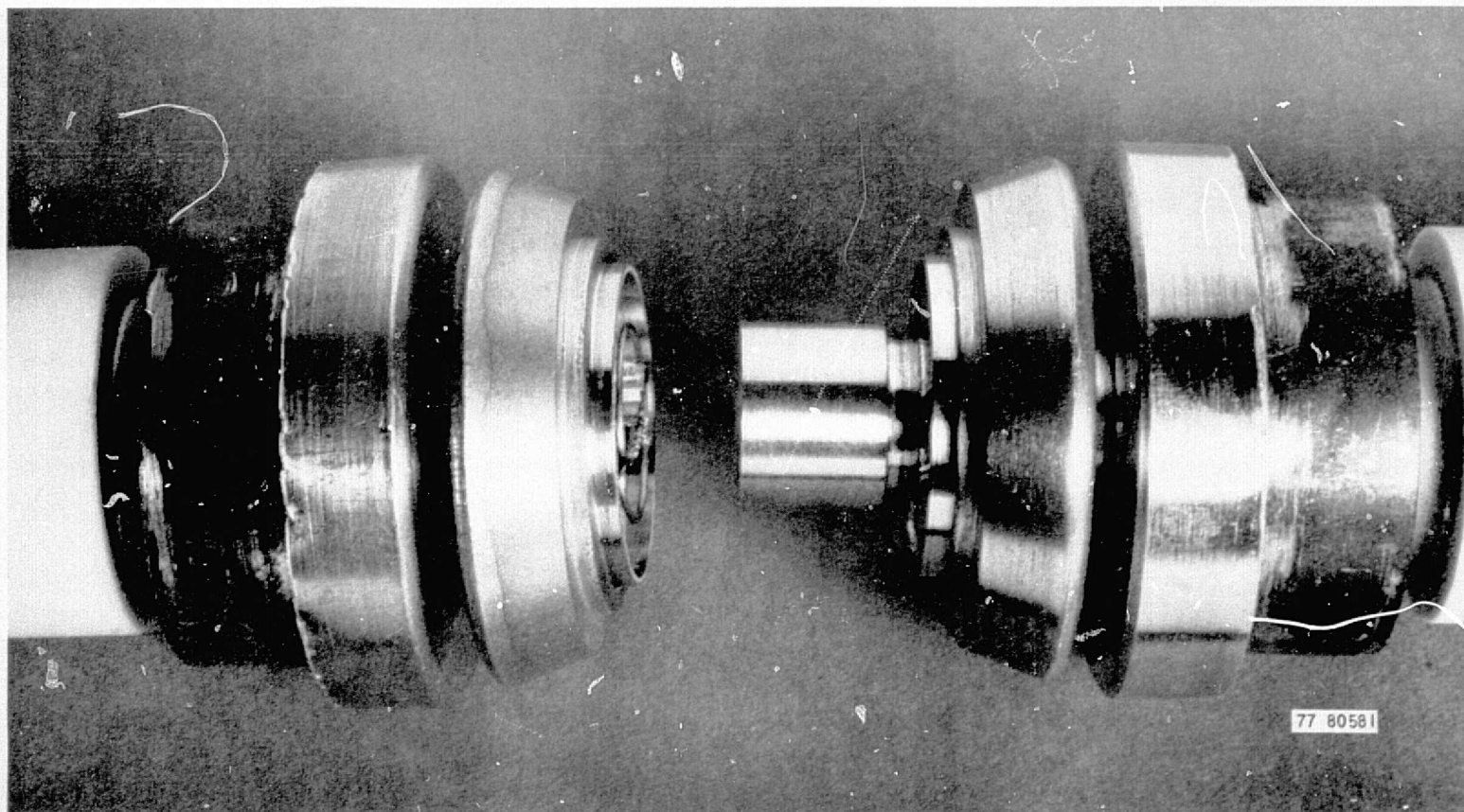


Figure 2-34. Side view of the QKS1875B halo cathode mounted on the tail-pole piece assembly together with a view of the platinum clad cathode mounted on the cathode pole piece assembly.

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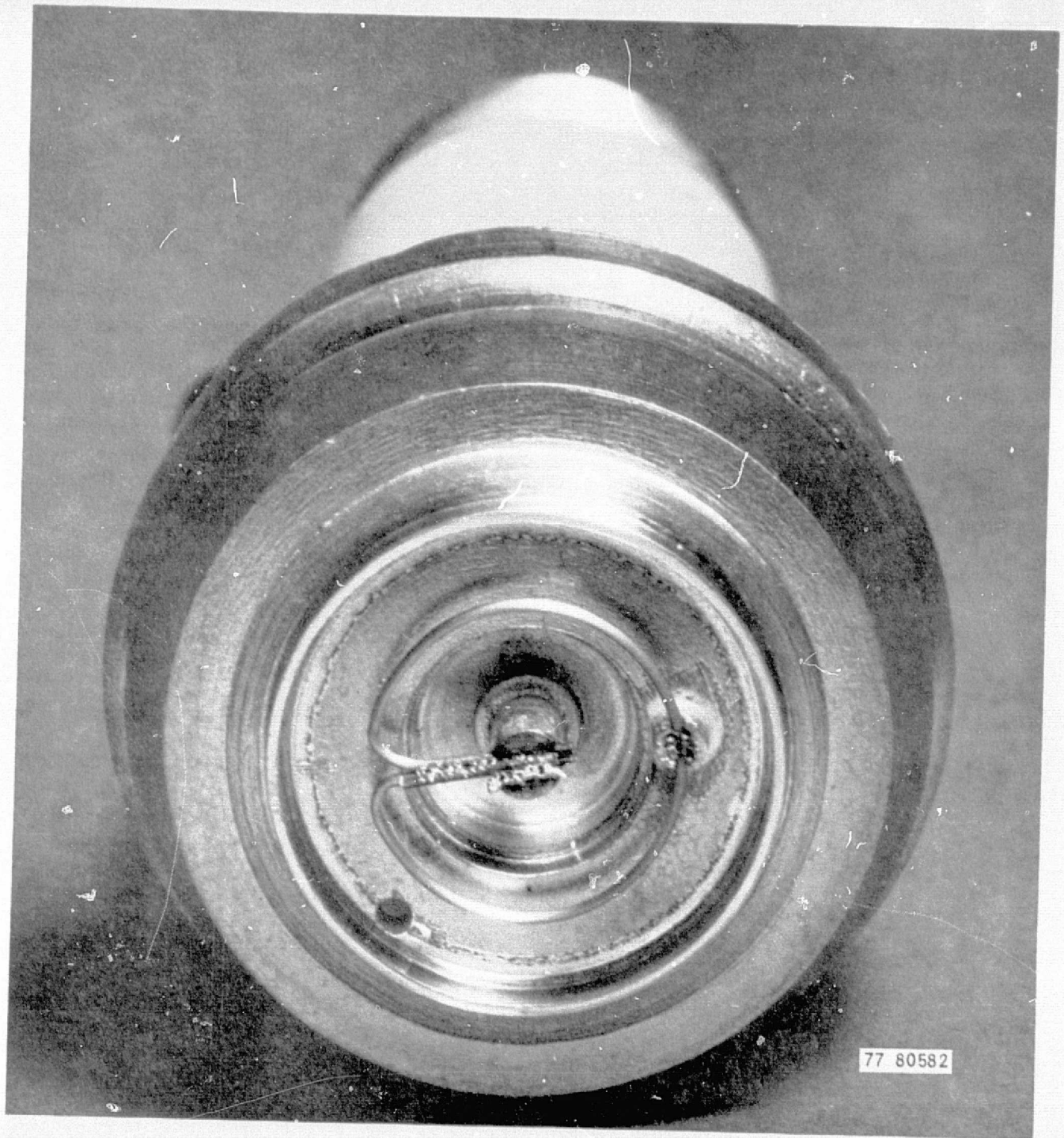


Figure 2-35. Top view of the halo cathode assembly in the QKS1875B.

there was not a normal flow of current from the cathode to the anode, and that there was no operation of the kind wanted.

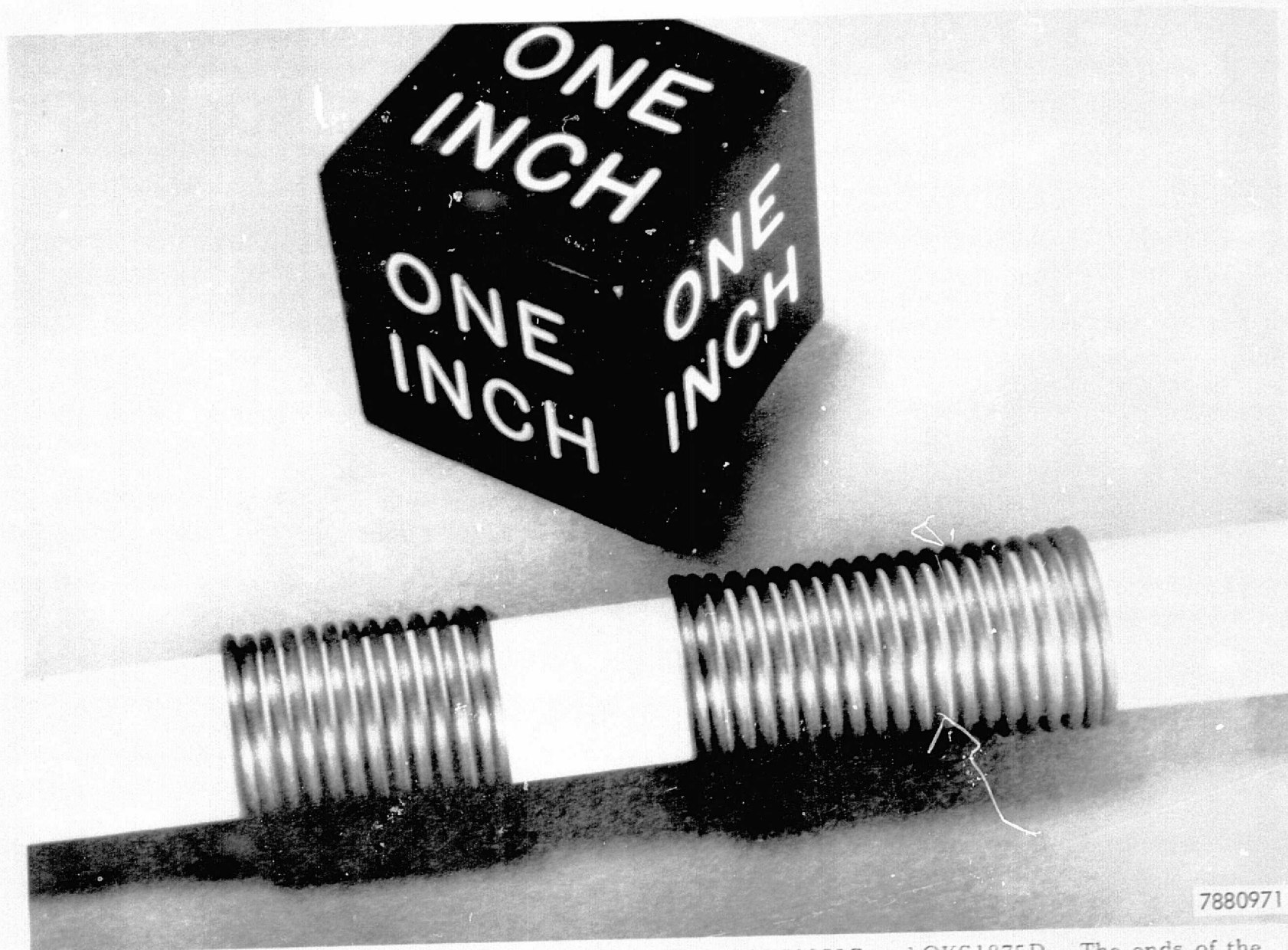
In anticipation that the starter cathode might not solve the problem, effort had already been initiated on a tube design with a tungsten helix used as a thermionic emitting cathode. The QKS1875 basic design which featured electrically isolated and water cooled internal magnetic pole pieces made it easy to install such a tungsten helix for a cathode. In addition to the normal arrangement of operating the pole pieces at cathode potential, a set of end shields of normal geometry with respect to the anode and cathode were added as a precaution against the axial flow of current that had been observed in QKS1875A and B designs. The pole faces were also cut back 0.100 in. each as in the QKS1875B design. The resulting tube design was denoted as the QKS1875C.

The form of the tungsten filament is shown in Figure 2-36. The shorter filament is for the QKS1875C and the longer one for the QKS1875D. The geometrical arrangement of the C design in the cathode and pole piece region is shown in Figure 2-37. No other changes were made from those discussed and indicated on the drawing.

2.6.3 QKS1875D Modifications Resulting from QKS1875C Test Data

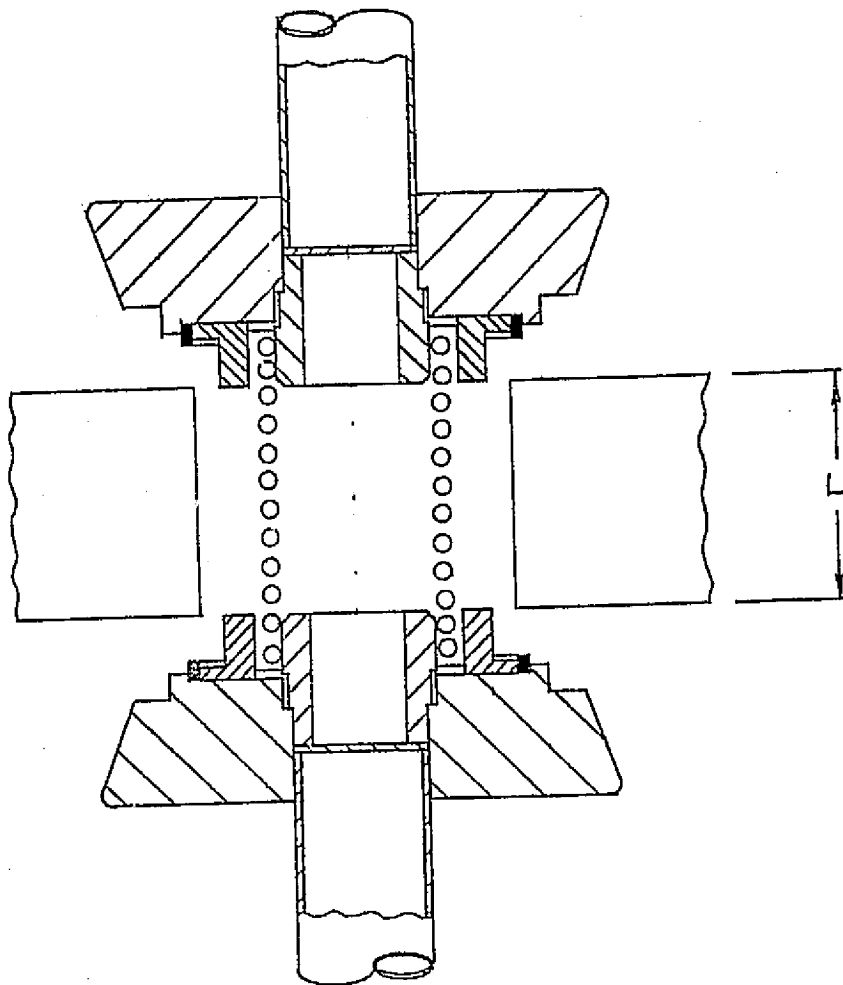
A considerable amount of test data was obtained from QKS1875C, and this data is the principle content of Section 2.5. One very obvious deficiency of the tube was its low gain and low level of microwave power output. This was felt to be caused in part by the relatively short length of the anode and cathode and the presence of the end shields on the cathode which would shield regions of the cathode near the end shields from the potential on the anode. If these were the principle reasons for the low gain and power output, the situation could be greatly improved by making the cathode and anode longer. Therefore the anode and cathode length were changed from 0.400 in. to 0.700 in. The balance of the design was not changed as indicated on Figure 2-37.

Other changes having to do with secondary emission from surfaces not normally involved in tube operation were made in QKS1875D. All of the previous designs had had trouble with a phenomenon that resembled a magnetron diode in which the diode draws progressively higher current at progressively lower voltages. However, a considerable amount of data indicated that the regular Amplatron cathode was not involved. This led to the conclusion that the diode must be elsewhere in the tube. To some extent the phenomenon was sporadic, depending upon how long the tube has been run, and in one case disappeared when the tube had been repumped and reprocessed. (QKS1875C). These observations led to the belief that secondary emitting surfaces in the tube must be involved, since magnetron diode interaction involving cold cathodes necessitates surfaces with secondary emission ratios greater than unity. Therefore, steps were taken in QKS1875D to use titanium end shields, and to spray the inner pole pieces with titanium, to eliminate these elements from initiating extraneous and unwanted magnetron diodes activity.



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Figure 2-36. The tungsten filament cathodes used in the QKS1875C and QKS1875D. The ends of the tungsten helics were "screwed" onto projections from the cathode and tail pole piece.



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TUBE DESIGN	L
QK 1875C	0.400"
QK 1875D	0.700"

Figure 2-37. The modifications of the baseline design that resulted in the QKS1875C and QKS1875D designs. The changes involve the tungsten helix and the use of end shields that are separated by a distance approximately equal to the anode length.

QKS1875A

DESIGN & CONSTRUCTION FEATURES

- PLATINUM CATHODE
- .600" MAGNETIC GAP
- .400" LONG ANODE
- NEGATIVE POLE PIECE FACES
- BIG FOOT OUTPUT CONNECTIONS

TEST RESULTS

- STARTING DIFFICULTIES
- SOME EVIDENCE OF EMISSION FROM POLE FACES TO ANODE
- OUTPUT PIPE FAILURE TERMINATED TESTS

Figure 2-38. Summary of Test Results and Design and Construction Features of the QKS1875A.

QKS1875B

DESIGN & CONSTRUCTION FEATURES

- * ● STARTER HALO CATHODE
- * ● 0.800" MAGNETIC GAP
- PLATINUM CATHODE
- .400" LONG ANODE
- NEGATIVE POLE PIECE FACES
- BIG FOOT OUTLET CONNECTIONS

* NEW FEATURES

TEST RESULTS

- TUBE WOULD DRAW CURRENT WITH MAGNETIC FIELD APPLIED AND EXCITED WITH EITHER MICROWAVE DRIVE OR EMISSION FROM HALO CATHODE. CURRENT WOULD INCREASE AND RUN AWAY
- SEVERE BOMBARDMENT OF HALO CATHODE AND POLE PIECES INDICATING AXIAL MOTION OF ELECTRONS
- NO OBSERVABLE GAIN
- TUBE FAILED DUE TO OUTPUT CERAMIC RUPTURE

Figure 2-39. Summary of Test Results and Design and Construction Features of the QKS1875B.

QKS1875C

DESIGN & CONSTRUCTION FEATURES

- * ● TUNGSTEN PRIMARY EMITTING
HELIX FILAMENT
- * ● CONVENTIONAL END SHIELDS
- .800" MAGNETIC GAP
- .400" LONG ANODE
- NEGATIVE POLE PIECE FACES
- BIG FOOT OUTPUT CONNECTORS

* NEW FEATURES

TEST RESULTS

- OPERATED AS AN AMPLIFIER. HIGH
SIGNAL TO NOISE RATIO PERFORMANCE
AS AN AMPLIFIER
- HIGHEST EFFICIENCY ATTAINED WAS
70%
- LIMITED IN GAIN AND POWER OUTPUT
- TUBE WHEN FIRST PUMPED EXHIBITED
RUNAWAY PHENOMENA
- TUBE WHEN REPUMPED DID NOT
EXHIBIT RUNAWAY PHENOMENA
- TUBE OPERATED AS BOTH A FORWARD
WAVE AND BACKWARD WAVE AMPLIFIER

Figure 2-40. Summary of Test Results and Design and Construction Features of the QKS1875C.

QKS1875D

DESIGN & CONSTRUCTION FEATURES

- * ● .700" LONG ANODE
- * ● 1.100" MAGNETIC GAP
- * ● CONVENTIONAL END SHIELDS MADE FROM TITANIUM
- * ● POLE PIECES SPUTTERED WITH TITANIUM
- * ● IMPEDANCE MATCH TO EXTERNAL CIRCUITS MODIFIED
- TUNGSTEN PRIMARY EMITTING HELIX FILAMENT
- NEGATIVE POLE PIECE FACES
- BIG FOOT OUTPUT CONNECTORS

* NEW FEATURES

TEST RESULTS

- BEING EVALUATED AT TIME OF CONTRACT CONCLUSION
- FILAMENT SAGGED AT HIGH OPERATING TEMPERATURES MAKING A SUCCESSFUL TEST AND EVALUATION DUBIOUS

Figure 2-41. Summary of the Design and Construction Features of the QKS1875D.

The QKS1875D was constructed and placed on test. However, the filament sagged badly while heating it up to the point where a small amount of primary emission could be obtained. X-ray photographs confirmed this sagging but indicated that the cathode was axially still on center. Because of the probable short life of the cathode if it is heated to emitting temperature, it was decided to obtain as much data as possible from the tube with the cathode unheated before proceeding with tests involving thermionic emission from the cathode.

Some of these cold cathode tests have been very interesting. For example it has been found that cathode to anode current flow can be initiated with as small amount as 200 watts of injected drive power, and that operation can be continued after removing the rf drive at DC power input levels as low as 150 watts. The microwave drive apparently has little impact other than to initiate oscillations which occur at discrete intervals over a very broad band of frequencies.

A brief summary of pertinent design features and performances of the various QKS1875 Amplitron designs is given in Figures 2-38 through 2-41.

2.7 Preliminary Investigation of Causes of Low Gain, Low Power Output, and Lower Efficiency than Expected.

The purpose of this section is to report upon a preliminary investigation of the causes for the low gain and power output of the QKS1875C design, and also for the lower efficiency than expected.

The conclusion that was reached is that there are probably two principle causes of the low gain and power output. The first of these is that the scale of the QKS1875C tube on which all the performance data was taken may be too small to provide an adequate safety factor in meeting the specifications for gain and power output. The scale of the untested QKS1875D, however, should be quite adequate. The second and more important cause is probably the unusual field pattern in the cathode-anode interaction area.

It is also concluded that the unusual field pattern in the cathode-anode interaction area is a principle cause of the lowered efficiency.

The body of assumptions, observational experience, and analytical reasoning for reaching these conclusions is summarized in the following material.

1. In the interaction area between cathode and anode, a radial electric field of the proper phase with respect to the space charge spoke is necessary to counteract the debunching forces of the space charge in the spoke and to prevent it from breaking up. This is normally provided by the traveling wave of microwave energy on the circuit, but contaminating radial fields from end cavity resonances and other sources can add or subtract to the normal radial fields and impact the power level at which the space charge breaks up.

2. The breakup of the space charge spoke is of a sudden, catastrophic nature. The tube is operating normally with a clean output as the DC power input is raised until a value is reached where the input drive no longer controls the output and the output becomes random noise. Because this boundary is so sharp the power output level at which it occurs may be precisely observed and recorded.

The experimentally observed relationship (figures 2-31, 2-32) of the maximum microwave power output that can be obtained for a given microwave power input is:

$$P_o \text{ (max)} = \frac{K^2}{4} + K \sqrt{P_i} + P_i \quad (13)$$

The value of K may be computed from any two experimental data points for $P_{i \text{ rf}}$ and $P_{o \text{ rf max}}$.

3. An additional input is an analytically derived relationship, based upon the assumption of rigid and identical spokes of space charge, (22) that the relationship between microwave power P_{rf} at any point on the microwave slow wave circuit and the microwave power input P_i is:

$$P_{rf} = \frac{C^2 X^2 Z_o}{4} + CX \sqrt{Z_o P_i} + P_i \quad (14)$$

where Z_o is the characteristic impedance of the network and C is a variable depending upon space charge density, length of anode, and other parameters.

This relationship has been experimentally observed on special tube which have permitted probing along the length of the slow wave circuit (22) and by more detailed theory of the Amplitron.(21)

The similarity of this expression to (13) is obvious by indentifying K as $CX \sqrt{Z_o}$ and taking the highest possible value for C which depends upon the total space charge in the spoke.

4. Expression (14) is derived on the basis of the relationship

$$\frac{dP}{dx} = C \sqrt{P Z_o} \quad (15)$$

in which the term $\sqrt{P Z_o}$ determines the circumferential (as well as the radial) field with which the electrons interact to generate power. C is a term which is proportional to the total space charge in the space charge spoke.

5. Assuming that the radial field as discussed in item 1 prevents the break up of the space charge spoke and noting that this radial field is proportional to the square root of the power flowing on the network, the highest possible value of C is governed by the minimum power on the network which is at the input.
6. It is recognized that C is proportional not only to the space charge density in the spoke but also to the length of the spoke; that is, C scales as the anode and cathode length.
7. We are now in a position to scale the values of K on the basis of the circumferential length X_1 of the microwave circuit and the height (or length) L of the anode and cathode, and the characteristic impedance of the network and to compare the QKS1875C, QKS1875D, and the QKS1532. Fortunately all of these tubes have the same voltage scale; otherwise this would introduce another scale factor. As a reference for scaling, the QKS1532 will be used and here the length of anode, length of circuit, and Z_0 have all been normalized to 1, which gives us the value of 194 for K if the power is in watts. The comparison is carried out in Table 2-3.
8. Several important observations can be made from this table: (1) on the basis of the scaled value of 88.4 for K, and the use of equation (13) the QKS1875C should have produced 4428 watts of output at 500 watts of drive rather than the 1300 watts that was produced, and which established the experimentally observed value of 25.6 for K. (2) at 1000 watts of drive the QKS1875C should have produced 5746 watts of power output, and (3) on the basis of the scaled value of 158.6 for K, the QKS1875D should produce 12,200 watts of power.
9. There is therefore a large disparity between the performances predicted for the QKS1875C on the basis of scaling from the performance of the QKS1532 and the experimentally observed performance. The major reason for this is believed to be the unusual field pattern that has been observed in the A, B, C and D versions of the QKS1875 design.
10. Field patterns in the interaction area are taken by rotating a probe which protrudes from a dummy cathode as shown in Figure 2-42. The electrical and mechanical test set up are shown in Figure 2-43. Ideally the cathode is at microwave ground potential in the operating tube and ideally the only potential on the slow wave structure is caused by the power flowing on the network in the normal mode. Figure 2-43b illustrates an arrangement for taking patterns without the complication of the presence of the end covers, but frequently it is the end covers that are the source of contaminating patterns. The poor patterns with which we are concerned persisted with the comparatively simple geometry shown in Figure 2-43b.

TABLE 2-3

Tube Type	Effective* Anode Length L	Circuit Length X_1	Z_o **	C_{max}	$K=LX_1 Z_o C_{max}$ Predicted from QKS1532	K Experimentally Observed
QKS1532	1	1	1	194.	Not Appl.	194.
QKS1875C	0.8	.73	0.78	155	88.4	25.6
QKS1875D	1.4	.73	0.80	271	158.6	none

* The selection of the anode length L is somewhat arbitrary. In the QKS1532 the voltage on the slow wave circuit that produces the radial field drops off in the axial direction from the tube center as a cosine function, while the end shields in the QKS1875C exert a serious shielding influence so that the effective anode length is shorter than the physical length.

The comparison relationship between the QKS1875C and D is somewhat better but the adverse influence of the end shields on the value of K is proportionately greater for the C than the D version.

** Approximate value of Z_o in QKS1532 was 120 ohms. Computed value for QKS1875C and D were 73 and 77 ohms, respectively, given in Section 2.4.2.

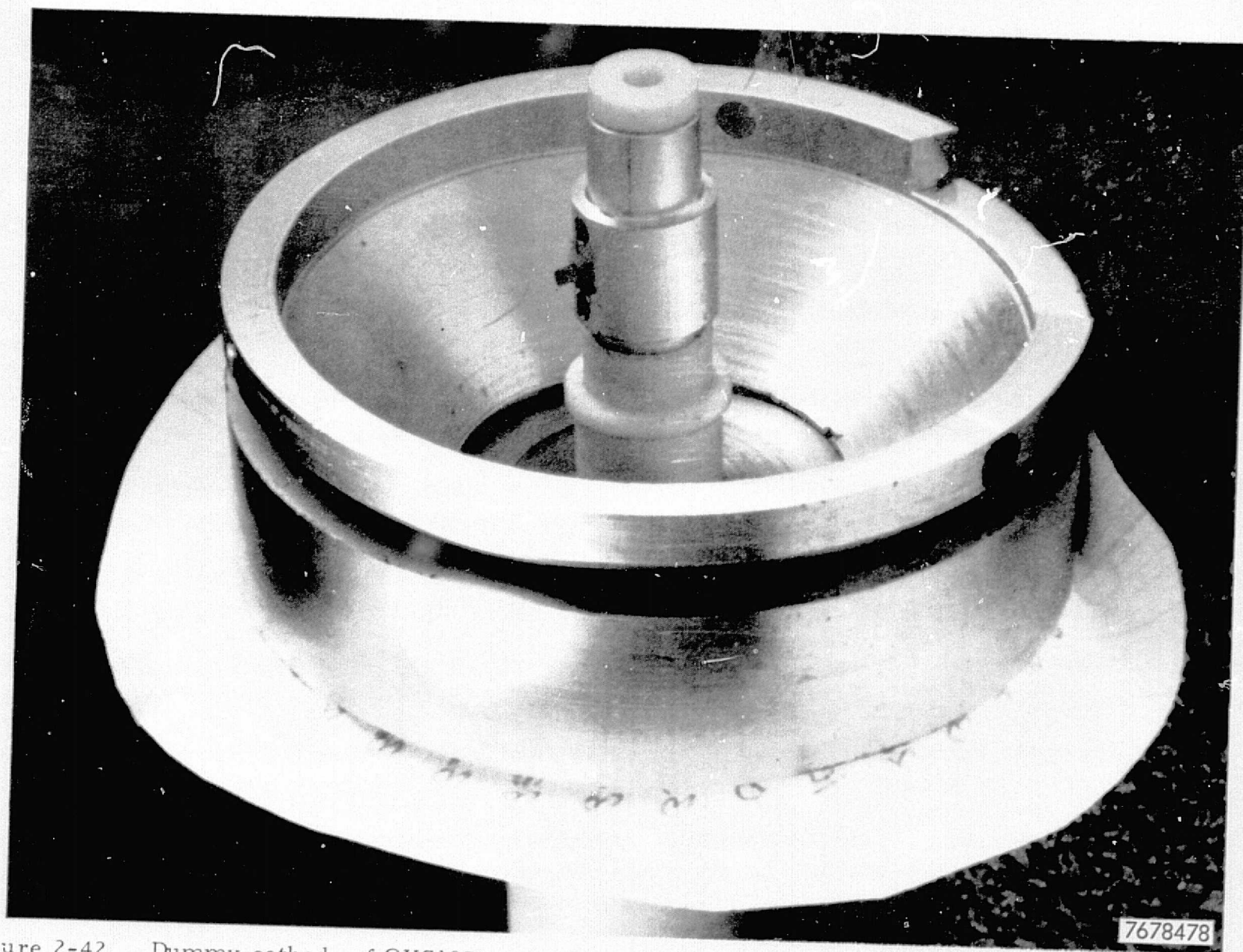
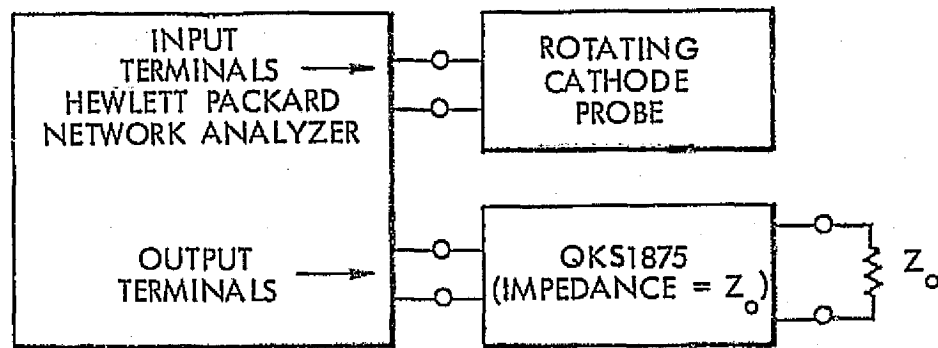


Figure 2-42. Dummy cathode of QKS1875 fitted with a probe for sensing the radial fields between the cathode and anode. The signal that is picked up is fed into the input port of a network analyzer and compared with the phase and amplitude of the signal at the output port of the analyzer which excites the network.



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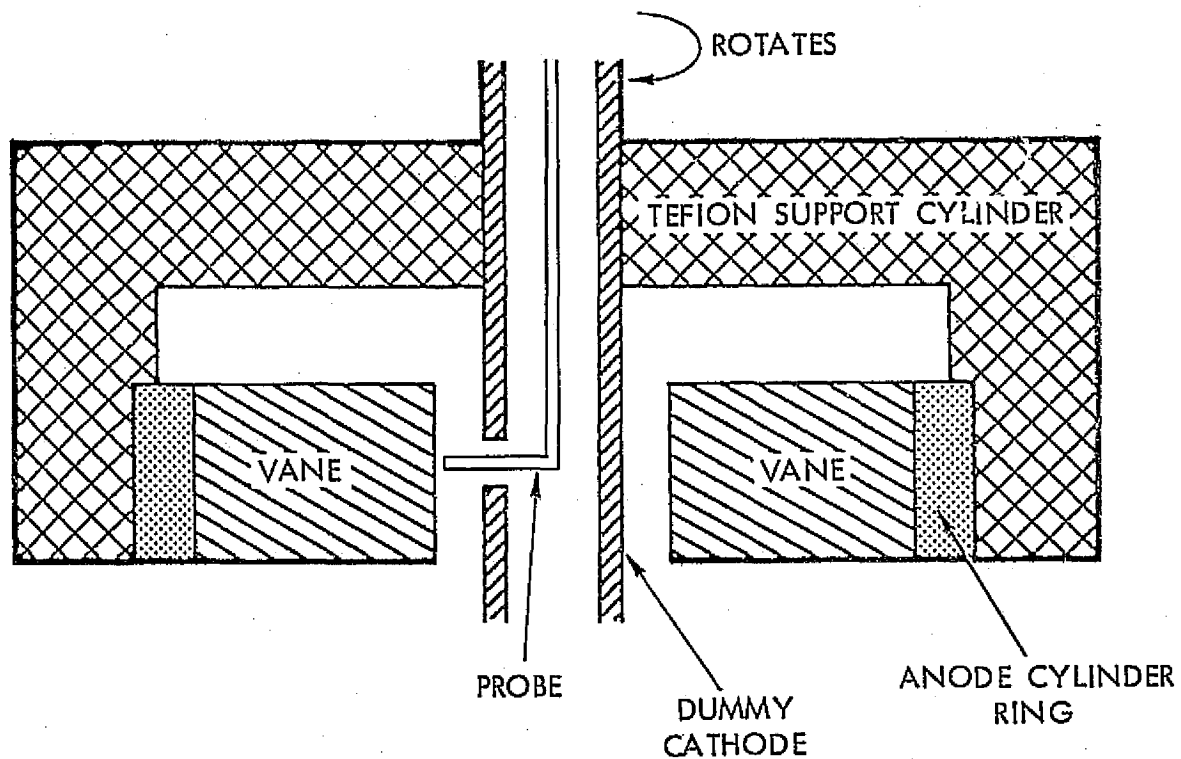


Figure 2-43a and b. Electrical and mechanical schematic of the pickup probe and its use.

11. The probe as shown in Figure 2-42 is sensitive to radial fields only. If the only source of radial fields is that caused by normal power flow along the slow wave circuit then the radial field is also a measure of the circumferential field which extracts energy from the motion of the electrons as they move against the circumferential field. However, the radial field is the force which pushes the electrons into spokes, often called "phase focusing" and prevents the break up or dispersion of the spoke in a circumferential direction.

The radial field can be substantially altered by contaminating fields associated with end cavity resonances, unbalanced couplings to the slow wave network, and higher order modes of the network itself. These contaminating fields nearly always have a radial field that is nearly as strong at the cathode as at the anode, as distinguished from the radial field established by the legitimate mode of propagation along the network which falls off exponentially in the direction of the cathode. The contaminating modes therefore have a relatively strong influence in the root area of the spokes.

12. The variety and nature of these contaminating field patterns have never been catalogued for the Amplitron, but there was a period of time in which they were studied in some detail for magnetrons and found to have a profound impact upon efficiency. An uncontaminated field pattern gave the best efficiency, and some badly contaminated field patterns reduced the efficiency by a factor of nearly two. After removing the contamination the efficiency was restored to its normal value.

While an examination of field patterns has not been pursued to any degree on crossed field amplifiers, it is interesting that some Amplitron designs give close to theoretical efficiency and others have an efficiency substantially less than theoretical.

13. The contaminating field pattern in the QKS1875 is such that the radial field as seen by the pick-up probe nearly vanishes at the input and output. A characteristic pattern is shown in Figure 2-44. Note the small difference in absolute potential between vanes 1 and 17 (between input and output of the slow wave network). Note also the sharp phase reversal seeming to indicate that the space charge spoke is subject to debunching radial fields as it traverses the gap between rf input and output.
14. The pattern of Figure 2-44 should be compared with a theoretical pattern as seen in Figure 2-45 where the electric field at the vane tips is described by

$$\vec{E} = e^{j\pi n(1+1/17)} \quad (16)$$

where n is the vane tip number starting with 1 and ending with 17.

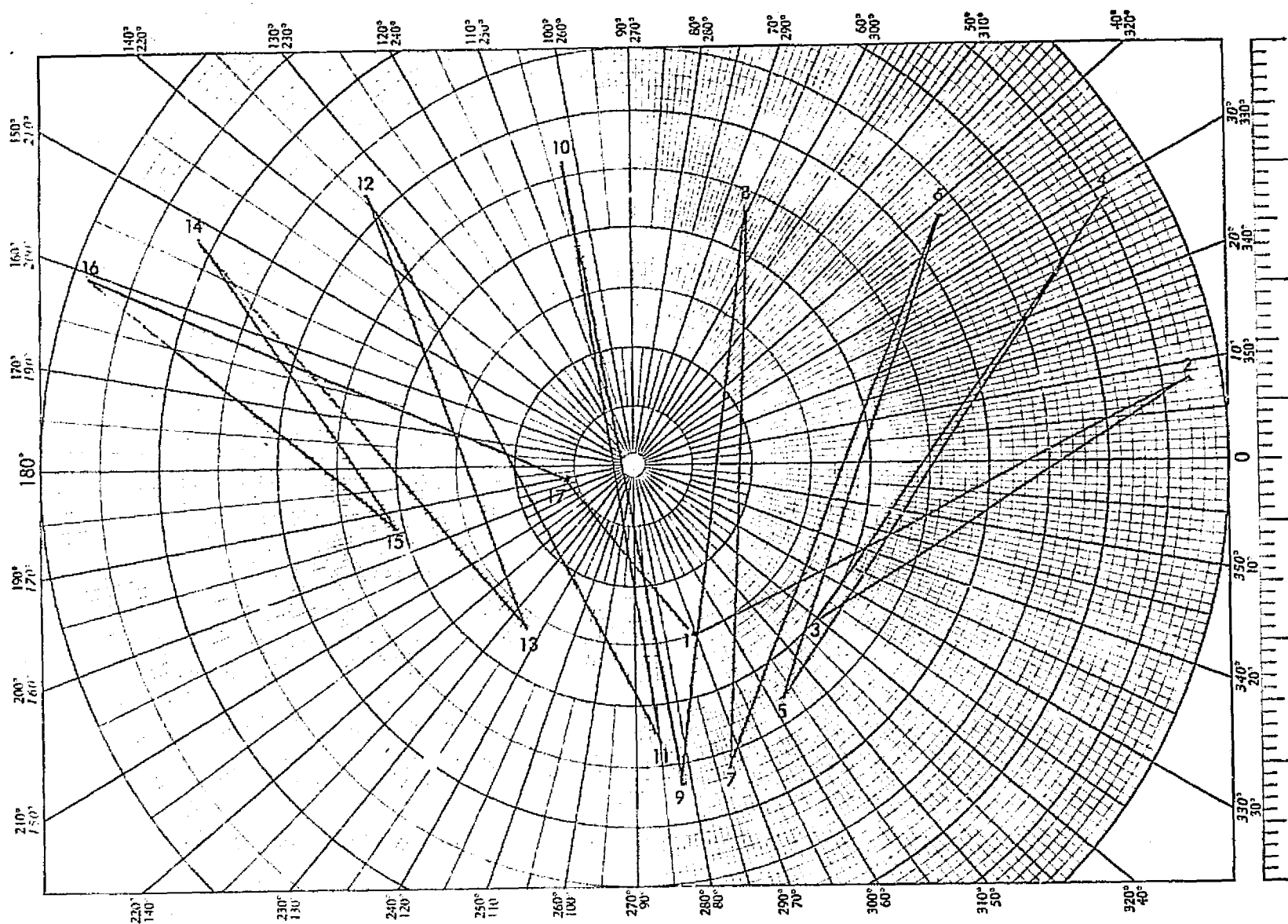


Figure 2-44. Typical field pattern obtained from the QKS1875 with the test set up of Figure 2-42. The numbers correspond to the vane tips, with numbers 1 and 17 straddling the gap between input and output connections.

15. The observed contaminating field pattern can be described as a radial field between cathode and anode which varies as

$$\overline{E} = \frac{-\cos n(n-1)e^{j\omega t}}{16} \quad (17)$$

This pattern can be observed by shorting out propagation in the slow wave structure by putting shorts between the straps at each cavity position.

16. If the maximum magnitude of the field distributions given by 16 and 17 is taken as unity, and if their sum is plotted, then the field pattern that results, as shown in Figure 2-46, looks very similar to that experimentally observed in Figure 2-44.
17. A reasonable amount of attention was given to finding the source of the contamination described by (17), including making some modification and dimensional changes to the structure, but a good field pattern was not obtained. End cavities were substantially eliminated as the source of the contamination at 2450 MHz; although they presented problems at other frequencies. And, of course, end cavities would not be present on the proposed space tube.

In the interests of not delaying the construction and test program, and perhaps not fully appreciating the potential impact that this unusual field pattern might have upon gain and maximum power output, it was decided to proceed to build tubes with the inferior field pattern.

18. The source of the contamination apparently lies in either the manner in which the input and output connections are made to the slow wave network, or in the mode pattern of slow wave network itself, or both.
19. In summary it is concluded that the most probable cause of low gain and low power output level is the unusual radial field pattern which reduces the radial voltage so much at the input of the tube as to allow the space charge in the spoke to break up after a critical space charge density in the spoke is reached. It is also concluded that the field pattern has an adverse effect upon the efficiency of operation. It follows that a correction of the field pattern should improve both the gain and the efficiency of the tube, perhaps dramatically.

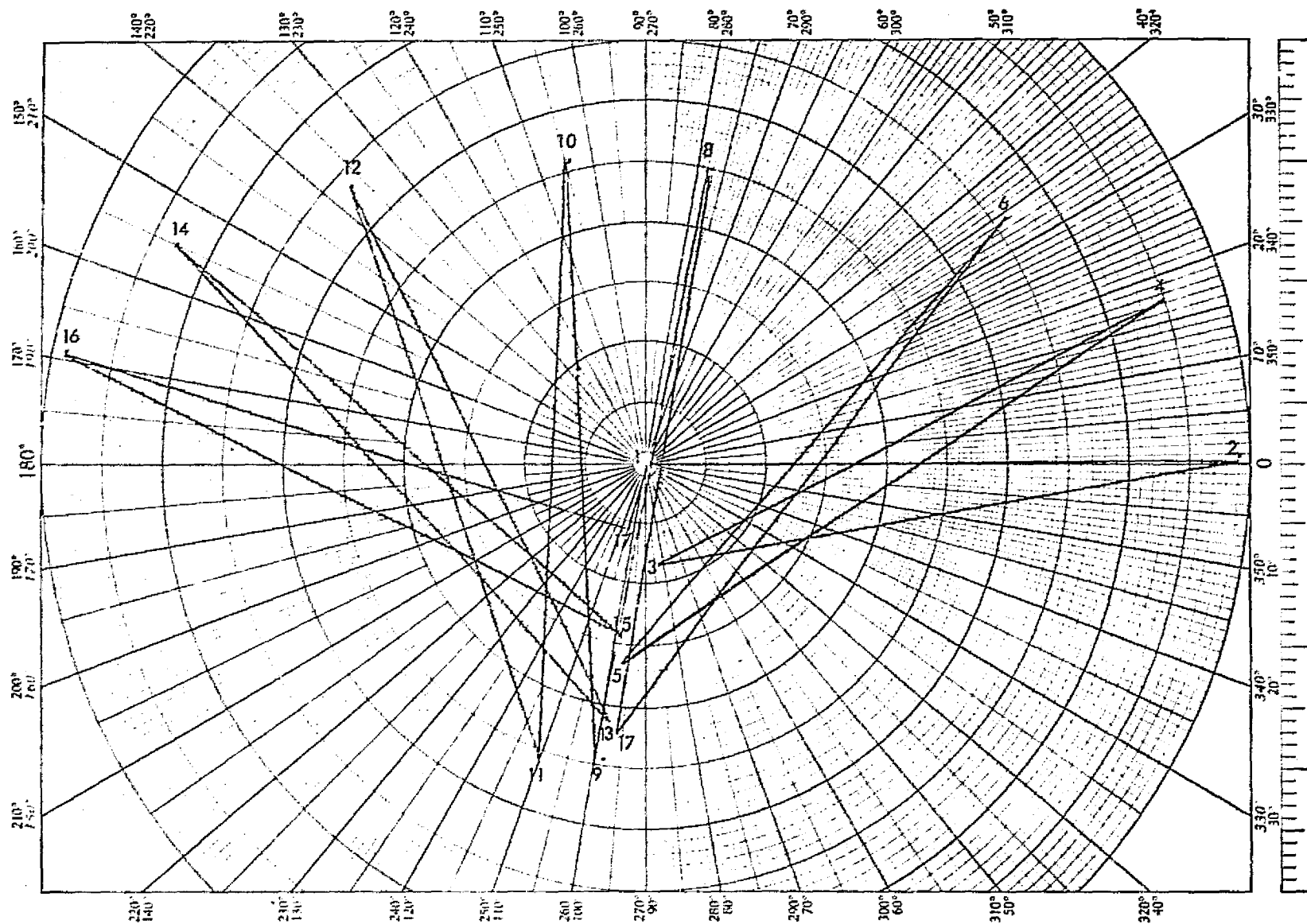


Figure 2-46. The field pattern as given by the sum of equations (16) and (17) indicate that the experimental field pattern has a substantial amount of contamination of the form given by equation (17).

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3.0 SUMMARY OF RESULTS ON QKS1875 AMPLITRON DEVELOPMENT

The objective of the work effort described in this report is closely related to meeting the requirements imposed upon a microwave generator by the power-from space concept in which microwaves are used to transmit energy captured from the sun by a satellite in synchronous orbit to the Earth's surface. These requirements include very high efficiency, very long life, capability for dissipating the heat generated by any inefficiency directly into space by passive radiation, very low emission of power at any radio frequency outside a guard band around the frequency allocated for the system, low mass requirements, and critical interfacing with the dc power input system.

Earlier studies had established a baseline design for the generator in its final configuration for use in space. The baseline design was arrived at after considering interfaces of the generator with the transmitting antenna, with the output of the dc power source generally considered to be a solar photovoltaic array, and with space as an absorber for heat resulting from any inefficiencies in the dc to microwave energy conversion process. The design tradeoffs that were made with the objective of minimum mass per kilowatt of radiated power output indicated a power level of five to ten kilowatts, a gain of five or six db, an efficiency of 85%, and a frequency close to the 2.45GHz selected for the SPS application.

Earlier system studies had also established the need for a very low level of noise at all microwave frequencies other than those very close to the main signal. There was very little data available which would indicate whether or not these requirements could be met with a crossed-field device.

The specific objectives of the work effort covered by this report were to design, construct, and evaluate a tube which would be consistent with meeting all of the longer range requirements of a space qualified tube for the SPS application, but which would be liquid cooled, would have a conventional vacuum envelope around it, and would have its magnetic field supplied by an electromagnet rather than by a permanent magnet. In the evaluation, the efficiency and noise behavior were to be of particular importance. The data obtained from the work effort was to be used as a basis for further refinement of the tube design and for a more accurate definition of the base-line design of the microwave power transmission system.

In the course of carrying out these objectives, it was also recognized that there would be the establishment of a test facility which could carry out the evaluation, and that a particularly important part of it would be a capability of making the required noise measurements. Such a facility, which features a very low noise-level drive source, has been established.

The results can best be summarized by considering them in the two categories of "test results" and "other important results":

TEST RESULTS

1. Signal to Noise Ratio

A signal to noise ratio of 69 db/MHz was obtained over a band of 2450 to 3450 MHz. The measurement of higher ratios was limited by the dynamic range of the spectrum analyzer, so that the tube may be potentially capable of significantly higher signal to noise ratios. Such measurements can be made but were prevented by the failure of output ceramic seal and the inability to suitably repair the tube before the conclusion of the work effort.

The noise measurement of 69db/MHz is significant in that it is the first measurement that has been made on a CW Amplitron or crossed field amplifier in such a broad frequency range, and because it is better than similar measurements that have been made on pulsed crossed field amplifiers. Although a considerable amount of additional data is needed, the preliminary results on signal-to-noise to noise ratio are considered highly significant, particularly when backed up by ratios of as high as 110db/MHz on conventional microwave oven magnetrons when operated without heater power and on DC power supplies. The Amplitron and magnetron are closely related in their energy exchange principles and therefore in noise generation.

2. Efficiency

The best overall efficiency obtained was 70.5%. Although the testing time given to accurately determining efficiency was limited, enough testing of a more general nature was done to indicate that significantly higher efficiencies from the QKS1875 were unlikely. It was concluded from microwave field patterns that were taken between the cathode and anode on cold test models (without a vacuum envelope around the tube) that a significant part of the departure from the expected efficiency of 80 to 85% efficiency was associated with the poor quality of these patterns.

The circuit efficiency was carefully measured on the finished tube with full microwave drive level but no amplification and found to be better than 97% providing the coaxial to waveguide transitions, an unessential part of the space tube, were not included.

The circuit efficiency of the operating tube will be even better because much of the power that is generated is near the output terminal and does not have to flow through the entire slow-wave-circuit. Such high circuit efficiency is essential to the long range objectives of a highly efficient space tube, where an expected overall efficiency of 90% requires the contribution of such a high circuit efficiency.

3. Gain and Power Output

Maximum gain and maximum output are inseparably related in Amplitron devices. The maximum gain available decreases with an increase in microwave drive level. The established experimental relationship on Amplitrons which holds for the QKS1875 Amplitron developed under this contract is

$$P_o \text{ max} = \frac{K^2}{4} + K\sqrt{P_i} + P_i \quad (18)$$

where $P_o \text{ max}$ is the maximum power output

P_i is the microwave drive power

K is the coefficient for maximum power output

An unexpected outcome of the QKS1875 tube development is the very low value of K obtained experimentally with that projected from scaling procedures in which the QKS1532 had been used as the base device. The highest value of K obtained for the QKS1875 was 25.6 whereas it should have been near 88.4 on a scaled basis. Such a large discrepancy means that the target figure for a gain of 7 db. could be achieved with only 250 watts of power output, while the maximum gain that could be achieved with 1300 watts output was only 3.8 db. These latter data points were also the conditions for obtaining the 70.2% efficiency and very close to the conditions for the measurements of high signal to noise ratio.

From an analysis of the microwave field patterns in the interaction area between cathode and anode it is believed that the problem lies in a peculiar contamination of the pattern which allows the total radial electric field to drop to near zero at the input of the device.

Since it is the radial field and the correct phasing of that field that contains the space charge in the rotating spokes of space charge, it is believed that the space charge spoke breaks up at that location before there is enough space charge to develop the desired levels of power output.

4. Efficient Operation at Low Low Levels of DC Power Input.

One of the distinguishing features between pulsed and CW Amplitrons is the need for a very sharp "knee" in the observed relationship between DC voltage and DC current input. Efficient operation will not occur until the slope of this relationship becomes relatively flat, which of course is on the top side of the knee. A sharp knee means a very broad range of power output over which good efficiency will occur. It also means that the voltage scale of the tube can be relatively high which is desirable from several points of view in the SPS application.

A very gratifying result of the QKS1875 test is that the knee is very sharp, and indeed the efficiency is as good at 150 watts of power output as it is at much higher power levels.

There is no reason to believe that the sharp knee is associated with low values of gain or maximum power output, since a rounded knee merely represents a condition where large amounts of leakage current escape from the interaction area before the onset of normal operation. When normal operation occurs, most of leakage current vanishes. There is, however, the possibility that the leakage current that does remain may be associated with ancillary noise, and that the sharp knee may also be a requirement for low spurious noise output.

Sharp "knees" in previous CW Amplitron devices were achieved by operating the internal magnetic pole pieces at cathode potential. In addition to negative pole pieces, the QKS1875 Amplitron has normal end shields attached to the cathode at the top and bottom of the interaction area. It is possible that these additional end shields further reduce the leakage current and therefore are desirable.

5. Starting of Cold Cathodes by Microwave Power Injection

One of the advantages of using Amplitrons in the SPS application is their demonstrated ability to have electron emission from a pure metal cathode initiated by the microwave drive. This feature eliminates the requirement for a thermionic cathode which has life difficulties, as well as the requirement for a separate source of power for heating the cathode or filament.

However, even though the electrical size of the QKS1875 Amplitron was nearly the same as that of a successfully operated QKS1532, which also had a pure metal platinum cathode and which could be started with less than one kilowatt of drive power, there was no indication of starting, even at a drive level of two kilowatts. The reluctant behavior of the QKS1875 in this respect is not understood but it may be related to the poor field pattern and to the low gain of the device at high power operating levels.

This failure of the original cold cathode device to start with microwave drive motivated the substitution of a directly heated tungsten cathode of the helix type. The gain and the power limitations of the device were then discovered.

The whole area of cathode starting in an Amplitron device is a complex one. Simple theory based upon initial power flowing on the network creating a field and reacting with stray electrons to bombard the anode and initiate current flow requires a large amount of power and is therefore inconsistent with observations of tubes such as the QKS1532.

There is a possibility that current flow is initiated by other mechanisms in the tube but these are not clearly understood.

Under any circumstances, it should not be concluded that a cold platinum clad cathode cannot be designed into the SPS application.

OTHER IMPORTANT RESULTS

1. New Approach to Attaching Input and Output Transmission Lines

The SPS application of the Amplitron has placed some unusually severe restrictions on attaching the input and output connections. Normally attachment on Amplitrons is accomplished by balanced transmission lines that connect the strapped anode to ridged waveguides. For high power levels the transmission line is liquid cooled. The arrangement is not compatible with solid vanes which are essential in the SPS application to transfer dissipated power from the interaction area to a symmetrical external cooling radiator.

A large amount of effort was devoted to a new approach in which the input and output connections were coupled to the top of the vanes at an angle which would not interfere with either the magnetic circuit or with the transport of heat from the front to the back of the vanes. Mechanically, the coupling is sufficiently large to handle power levels of up to ten kilowatts. Areas are large enough to minimize microwave skin losses while providing a large cross sectional area to conduct dissipated power to the vanes for transfer to the external radiator.

The normal narrow bandwidth of top-of-the-vane coupling occasioned by a large ratio of input inductive reactance to resistive component has been eliminated by the use of a balanced coupling which greatly reduces this ratio. However, there is a possibility that the new arrangement in its present detailed configuration may be the cause of the poor field pattern. If this is the case, then it must be configured differently as the poor field pattern cannot be tolerated because of its impact upon efficiency and probably upon the low gain performance of the tube at high power output levels.

2. Conventional Vane and Strap Slow Wave Circuits for Amplitrons

The QKS1875 represents the first time that conventional strap and vane techniques have been used on Amplitrons. If successful the impact of this arrangement upon the future direction of Amplitron development will be considerable. The construction is a very economical one as evidenced by the millions of microwave oven magnetrons that are produced every year. And it is also a construction that can be conductively cooled.

RECOMMENDATIONS FOR FUTURE EFFORT

1. The concentration of the work effort upon the design and construction of the test models, and the failure of the early cold-cathode models to operate, resulted in a truncated test program which did not fully evaluate the QKS1875C and 1875D models which were the last to be constructed. It is therefore recommended that the last two models be subjected to more testing. In the case of the QKS1875C model, this will involve repumping the tube, and in the case of the QKS1875D model, this may involve replacing the filament in the tube before a full evaluation can be made.
2. The design of the QKS1875 slow wave circuit and the coupling arrangement of the input and output to the slow wave structure should be thoroughly reviewed to understand the poor microwave field pattern in the interaction area. Then, if necessary, either the slow wave circuit or coupling arrangement, or both, should be revised to obtain a good field pattern. Hot tubes should then be constructed and evaluated.
3. In view of a growing trend to think of on-board maintenance of tubes in space for the SPS, the use of a primary emitting cathode should be reconsidered. The desired type of cathode would be one that would start on secondary emission with microwave drive but which would then heat up from back bombardment and operate mainly on primary emission.

Based upon data obtained from magnetrons that operate with a tungsten filament cathode, the backbombardment power on such cathodes is 1% of the DC input power or less. In the space applications this would allow the cathode to radiate heat caused by backbombardment to the anode and eliminate the cathode cooling radiator which is considered essential for a pure metal cathode that requires a higher percentage of backbombardment power to obtain the required emission level.

Such cathodes would not have the potential infinite life of pure metal secondary emitting cathodes but they could have many years of life, particularly in the zero gravity of space which would prevent sagging from gravitational forces. They could probably be replaced by a single plug in arrangement.

The additional two or three percent efficiency advantage that tubes employing such cathodes would have should not be overlooked. A 92% efficiency tube has definite advantages in mass per kilowatt of power output over a 90% efficiency tube which has thus far been considered as the ultimate objective after incorporating the refinements necessary to peak the efficiency.

4. The electrical size of the tube should be reviewed. The extremely sharp knee on the voltage current characteristic of the QKS1875 Amplitron and the good efficiency at low values of power output indicate that the tube could be electrically scaled to higher voltages and power level without sacrifice in efficiency. A higher microwave drive level associated with a higher power tube would make the starting of an initially cold cathode easier. The tradeoffs with a much larger and more complicated cooling system would need to be examined. Passively cooled tubes with a power output of fifteen to twenty kilowatts are seen as a possibility. Much higher power tubes are possible with an active cooling system.

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